DTIC FILE COPY

ESL-TR-86-60
VOL I

FIRE SUPPRESSION BY HALON 2402, VOLUME I OF II

M. PLUGGE, R.E. TAPSCOTT, H.D. BEESON, D. ZALLEN,
J.L. WALKER, P. CAMPBELL

NEW MEXICO ENGINEERING RESEARCH INSTITUTE
BOX 25, UNIVERSITY OF NEW MEXICO
ALBUQUERQUE NM 87131

OCTOBER 1987

FINAL REPORT
SEPTEMBER 1984 - JUNE 1986

DTIC
ELECTE
DEC 1 2 1988
S D
C&D

AFESC

ENGINEERING & SERVICES LABORATORY
AIR FORCE ENGINEERING & SERVICES CENTER
TYNDALL AIR FORCE BASE, FLORIDA 32403

NAVAIR

NAVAL AIR SYSTEMS COMMAND
DEPARTMENT OF NAVY,
WASHINGTON DC 20361

88 12 9 002

Best
Available
Copy

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
Unclassified	
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT
	Approved for public release.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	Distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
NMERI WA3-26 (3.02)	ESL-TR-86-60, Volume I

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
New Mexico Engineering Research Institute	NMERI	Engineering and Services Laboratory

6c. ADDRESS (City, State and ZIP Code)	7b. ADDRESS (City, State and ZIP Code)
Box 25, University of New Mexico Albuquerque, New Mexico 87131	Air Force Engineering and Services Center Tyndall Air Force Base, Florida 32403

8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
HQ AFESC/RD and NAVAIR	RDCF	Contract No. F29601-84-C-0080

8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS.			
Tyndall AFB FL 32403-6001	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
Commander NAVAIR Washington DC 20361-5510	64708F	2505	10	22

11. TITLE (Include Security Classification)
FIRE SUPPRESSION BY HALON 2402, Volume I of II

12. PERSONAL AUTHOR(S) Martin Plugge, Robert E. Tapscott, Harold D. Beeson, Dennis Zallen, Joseph L. Walker, and Phyllis Campbell

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final Report	FROM 9/84 TO 6/86	October 1987	259

16. SUPPLEMENTARY NOTATION
Availability of this report is specified on reverse of front cover.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Halon firefighting agents Military specification,
13	12		Fire extinguishment testing. Environmental assessment (jcs)
04	02		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This Technical Report is divided into two volumes. Volume I consists of the front matter and text while Volume II consists of Appendices A - J. Fire testing shows that, in outdoor applications, the fire extinguishment capability of Halon 2402 is superior to that of Halon 1211 and 1301. The increase in effectiveness is due to better agent application properties (Halon 2402 is ejected as a liquid), better fuel-inerting capacity (lower vapor pressure), and improved flame suppression (possibly resulting from the presence of two bromine atoms). An environmental assessment shows no environmentally unacceptable properties; however, toxicity during agent use could be problematical.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS ☐	UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
JOSEPH L. WALKER	(904) 283-6194	HQ AFESC/RDCF

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE. UNCLASSIFIED

PREFACE

This final report was prepared by the New Mexico Engineering Research Institute (NMERI), University of New Mexico, Box 25, Albuquerque, New Mexico 87131, under Contract F29601-84-C-0080 (Subtask 3.02), for the Engineering and Services Laboratory, Air Force Engineering and Services Center, Tyndall Air Force Base, Florida 32403-6001, and Naval Air Systems Command, Department of Navy, Washington, D.C. 20361.

This is Volume I of a two-volume report. Volume I contains all of the text which includes testing, results, and conclusions. Volume II contains all of the appendix material, computer programs, data, instrument calibration, and the proposed military specification for Halon 2402.

The HQ AFESC/RDCF project officers were Mr Joseph L. Walker and Mr Bryce E. Mason. The NAVAIR project officer was Ms Phyllis Campbell. This report summarizes work done between September 1984 and June 1986.

NMERI scientists and engineers who contributed to testing and data interpretation in this project include Betty J. Humphrey, Mark L. Graham, Gerard A. Blahut, and J. Kent Newman. Special acknowledgment is due the project technicians, Susan H. Kellogg, Jimmy D. Watson, Jesse M. Parra, Dana R. Drake, Tracy A. Goss, Thomas M. Debevec, C. Tom Coulter, Bruce M. Willard, Brian D. McGill, Fwu-Lin Lii; Dr Ulrich Hollstein, Professor of Chemistry; and Dr Robert Royer, Research Associate.

When U.S. government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded, by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This Technical Report has been reviewed and is approved for public release.

JOSEPH L. WALKER
Chief, Fire Technology Branch

LAWRENCE D. HOKANSON, Col, USAF
Director of Engineering and Services
Laboratory

ROBERT R. COSTIGAN, Lt Col, USAF
Chief, Engineering Research Division

DTIC
COPY
INSPECTED
6

By
Distribution/

Availability Codes

Dist | Avail and/or Special

A-1

iii
(The reverse of this page is blank.)

TABLE OF CONTENTS

TABLE OF CONTENTS
(CONTINUED)

TABLE OF CONTENTS
(CONTINUED)

TABLE OF CONTENTS
(CONCLUDED)

LIST OF FIGURES

LIST OF FIGURES
(CONTINUED)

LIST OF FIGURES
(CONTINUED)

LIST OF FIGURES
(CONCLUDED)

LIST OF TABLES

LIST OF TABLES
(CONTINUED)

LIST OF TABLES
(CONCLUDED)

SECTION I
INTRODUCTION

A. OBJECTIVE

The objective of this effort was to conduct analytical and experimental investigations to define the capability of Halon 2402 as a firefighting agent. Applications and performance of Halon 2402 were to be compared to the well-known Halons 1301 and 1211. The data generated were to be used to establish a draft purchase specification for obtaining the agent. Defined within this study was to be a full test range for quality, safety, storage, purchase, handling, equipment type, performance, applications, and environmental impact.

B. SCOPE

The scope of this effort was a full range of experimental performance tests and analytical studies of dibromotetrafluoroethane ($C_2F_4Br_2$), Halon 2402. Tests were used to define its fire suppression and environmental performance through a complete range of conditions. Testing included small-, medium-, and large-scale fires. Performance of the $C_2F_4Br_2$ was determined and analyzed. Data were accumulated and used to evaluate hazards to personnel and the environment. Specific details of tests and results are found in Volume II which contains Appendixes A through J.

C. BACKGROUND

The newest series of clean and environmentally acceptable fire suppression agents is the vaporizing liquid agents group known as halons. Halons are hydrocarbons containing one or more of the halogen atoms fluorine (F), chlorine (Cl), bromine (Br), and iodine (I). Three halons noteworthy for a range of fire suppression applications are

Halon 1301 (bromotrifluoromethane), CF_3Br

Halon 1211 (bromochlorodifluoromethane), CF_2ClBr

Halon 2402 (dibromotetrafluoroethane), $C_2F_4Br_2$

1

Halon 1391, 1211, and 2402 are formed by replacing all the hydrogen atoms in methane (CH) or ethan (c H) with halogen atoms. A wide range of brominated, chlorinated, and fluorinated halocarbons was laboratory-tested at Purdue University (Reference 1). The fire suppresssion agents were the threee primary halons: Halon 2402 Halon 1301 and Halon 1211. However, this testing was conducted at laboratory scale. The following discussion indicates that the ordering of these three halons is highly dependent upon the application. Consider the physical data of the halons in Table 1. These data indicate that the relatively light Halons 1301 and 1211 could be wind-blown and buoyantly driven away so that Halon 2402 is a likely candidate for large outdoor fires. This is also supported by the boiling points of the agents. When Halon 1301 exits a nozzle, it is almost all vapor; Halon 1211 is about 75 percent liquid, which rapidly vaporizes; and Halon 2402 is all liquid and remains liquid at normal temperatures and pressures. Liquids give greater throwing range, directionality, and penetration; however, only vapors can mix with the air to provide an inerted volume which can suppress a directly or indirectly accessible fire. That the vapor pressure for Halon 2402 is less than atmospheric pressure, means that this halon can be transported in non-pressurized canisters and poured like water; however, it is 2.17 times heavier than H 0, and the neat vapors can be toxic.

The range of application for Halon 1211 might be expected to fall between Halon 1301 and 2402, but this has not been the case in the United States, where Halon 2402 has received little use. Halon 1301 and Halon 1211 are more heavily used in the United States because:
1. The United States is a manufacturer of Halon 1301.
2. Halon 1301 found the first major commerical application.
3. Halon 1301 and 1211 have had NFPA Standards since 1977.
4. The neat agent toxicity ratings are Halon 2402 and Halon 1211 Halon 1301.

Halon choice depends on the fire scenario. One can envision a scenario where items are burning in the front control panel of an aircraft cabin and a person with a firefighting agent is standing outside the entryway in the aisle. If the cabin can be totally flooded (inerted), then the clean low

TABLE 1. PHYSICAL PROPERTIES OF HALONS.[a]

Property	Halon 1301	Halon 1211	Halon 2402
Molecular weight	148.93	165.38	259.84
Boiling point at 1 atm, °F	-71.95	26.0	117.16
Freezing point, °F	-270.0	-256.0	-168.7
Critical temperature, °F	152.6	309.0	418.0
Critical pressure, lb/in.^{2}, abs	575.0	595.4	499.5
Critical volume, ft^3/lb	0.0215	0.0225	0.0203
Critical density, lb/ft^3	46.5	44.5	49.32
Specific heat of liquid at 77 °F, $\frac{Btu}{lb-°F}$	0.208	0.185	0.166
Specific heat of vapor at 77 °F at 1 atm, $\frac{Btu}{lb-°F}$	0.112	0.108	0.11
Heat of vaporization at boiling point, $\frac{Btu}{lb}$	51.08	57.0	45.25 (est.)
Thermal conductivity of liquid at 77 °F, $\frac{Btu}{h-ft-°F}$	0.024	--	0.027
Liquid viscosity at 77 °F, cP	0.15	0.34	0.72
Vapor viscosity at 77 °F, cP	0.016	0.013	0.0143
Surface tension at 77 °F, dyn/cm	4.0	16.5	18.0
Solubility of water in halon at 1 atm at 77 °F, percent by weight	0.03	--	0.008
Solubility of water in halon at 1 atm at 70 °F, percent by weight	0.0095	--	--
Relative dielectric strength at 1 atm at 77 °F at N_2 = 1	1.83	--	4.02
Retractice index of liquid at 77 °F	1.238		1.367
Density of liquid at 77 °F, lb/ft^3	96.01	112.2	135.0
Diffusivity in air at 1 atm at 77 °F, cm^2/s			0.0518 (calculated-- Leonard-Jones)

[a]References 2-5.

3

toxicity Halon 1301 is the agent of choice. A hand-held extinguisher containing Halon 1301 can also be used if the fire is small enough to be penetrated and extinguished with a low local volume concentration. However, Halon 1301 can be drafted away by wind or the buoyancy of fire. In this case, Halon 1301 may not get to the fire without high-pressure application equipment. The use of Halon 1301 may also significantly increase halon decomposition at the fire because the concentration may be low due to drafts and low penetration. Halon 1211, which is 75 percent liquid as it leaves the nozzle, provides increased throw range and, thereby, better fire penetration than Halon 1301. Halon 1211 may reach the fire front, knock down the fire, and also vaporize to provide for local partial flooding to indirect volumes such as under/inside the instrument panels. However, Halon 1211 needs to be applied with significant velocity to control drafting. All halon agents require that the necessary concentration for extinguishment be rapidly obtained at the fire volume and maintained at a sufficient extinguishing concentration because halons will decompose to yield toxic byproducts when near sufficient heat and fire at insufficient extinguishing concentration. Halon 2402 is a dense liquid; and the throw range of heavy liquids is greater than that of lighter, vaporizing liquids or vapors. Given equal effectiveness of the firefighting agent molecules, the firefighting capability in a volume of a liquid halon is much greater than the same volume of a gaseous agent. Therefore, liquid Halon 2402 not only provides a greater throw range to reach a fire and penetrate it, but also provides for rapid application of high halon concentrations at the fire. However, the great disadvantage is that Halon 2402 is much more toxic than Halon 1301 and 1211.

The fire protection engineer is then faced with a decision. Halon 2402, although more toxic, may reach a distant, drafty fire to suppress it; whereas, other halons may not reach the fire or may decompose yielding toxic byproducts. In addition, the other halons cannot inert liquid fuels for a sufficient time period. The use of a halon or any other firefighting agent is highly dependent on the application. Although most fires can be fought from upwind, and there are many significantly toxic products resulting from fire, the decision as to which halon to use can be very complex. People will often make mistakes, so the proper handling of any toxic or high-pressure agent will require continued training.

4

The evaluation of the extinguishing performance of Halon 2402 is very important because this will be used to define its practical applications and the associated exposures relative to toxicity. Very little data exist concerning Halon 2402, especially in practical applications for large-scale (greater then 150 ft^2) fires. Reference 5 contains a good summary of past experiments performed using Halon 2402. The need exists to evaluate the performance of Halon 2402, to define its practical application types, and to determine its environmental and safety impacts.

SECTION II
FIRE TESTING

A. SMALL-SCALE FIRE TESTING

The purpose of small-scale fire testing is to quantitatively measure agent requirements for extinguishment at the molecular level. The experiments described here have been reported elsewhere (Reference 6). The results are also presented in this report for completeness. The experiments were conducted in strictly controlled environments to assure test to test repeatability. These small-scale experiments provide the background necessary to develop practical large-scale experiments. The results provide a proportionality between the amount of agent required for fire suppression and permit simple molecular performance ratings. The tests were limited to Halons 1301, 1211, and 2402 due to their demonstrated high efficiency in air. Additional information with oxygen enriched and oxygen deficient fires using Halons 2402, 1301, and 1211 is also available (Reference 6).

1. Experimental Methods

Two types of test apparatus were used. The classical cup burner apparatus (Reference 7) was used to measure the agent concentrations required to extinguish flames in flowing atmospheres (Figure 1). A static, premixed atmosphere chamber was used to measure agent concentrations required to prevent ignition (Reference 8) of fuels (Figure 2). The static experiments generated data concerning agent requirements to prevent the spread of a fire from an ignition source to nearby fuel. Both types of experiments expanded on previously published test results.

The cup burner apparatus (Figure 3) consisted of a glass chimney surrounding a fuel cup supported by a tube stem which supplied fuel to the cup. A well-controlled atmosphere of oxygen, nitrogen, and vaporized halon was fed to the bottom of the chimney where it passed through a mixing bed of glass beads before flowing up the chimney past the fuel cup. The flow rate of each atmospheric component was measured using a rotometer with a ±5 percent accuracy prior to mixing. The gases used were ultra-high-purity 99.99 percent minimum oxygen and 99.999 percent minimum nitrogen. Heating
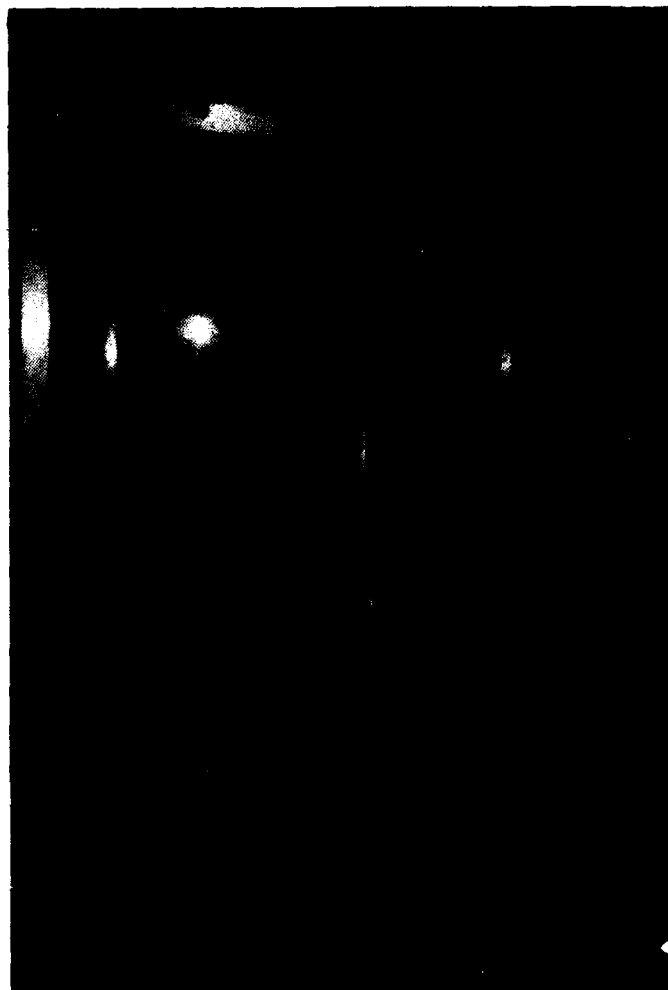
Figure 1. Cup Burner Apparatus Used in Small-Scale Testing at NMERI.

Front view

Rear view

Figure 2. Static Chamber Used in Small-Scale Testing at NMERI.
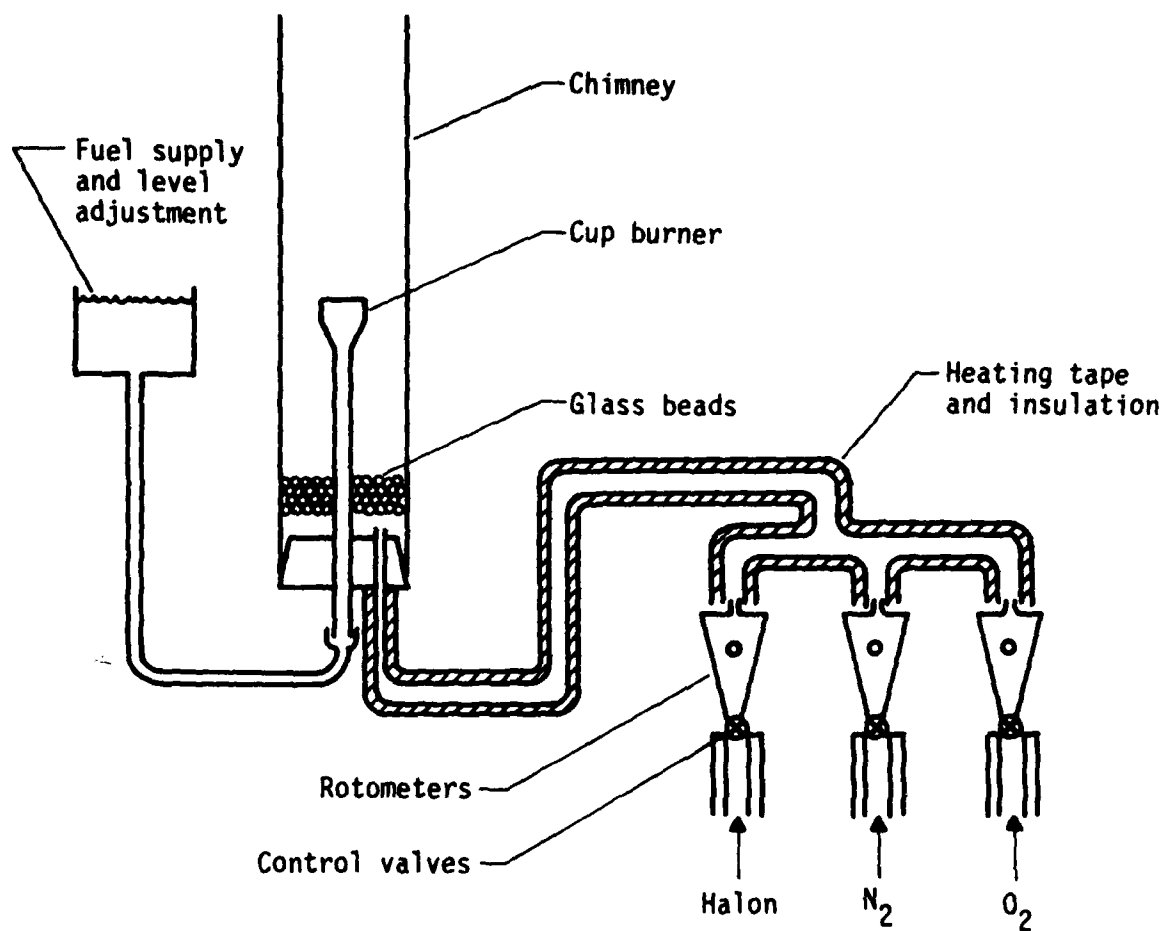
Figure 3. Components of Cup Burner Apparatus.

elements and insulation on the atmosphere supply lines were used to heat the incoming atmosphere for elevated temperature tests. The procedure for using the cup burner apparatus has been described in Reference 7.

The apparatus for the static chamber experiments consisted of a horizontal cylinder with a Plexiglas window at one end and a steel plate covering the other as shown in Figure 4. Gas/vapor supply lines, pressure lines, electrical lines, a fuel line, vents, and a pressure relief disc were connected to the steel plate. A fuel holder, an electric igniter coil, and a fan were located inside the cylinder. Insulation and heating elements were wrapped around the cylinder to maintain the Halon 2402 in the vapor phase during tests. The procedure used in conducting static chamber experiments has been described in Reference 8.

The first series of tests performed in different atmospheres demonstrated that the evaluation of ignition was not as clear-cut as expected. Short-lived, self-sustaining and non-self-sustaining flames were generated over a broad range of halon concentrations. A liberal definition of ignition was adopted for the majority of the tests. By this definition any flames produced, even those sustained by the igniter coil, were considered to be ignition. A number of tests were repeated at the end of the experiment using a more conservative definition of ignition. In these tests, the flame was required to be self-sustaining for ignition to occur. Tests using the more restrictive ignition criterion were expected to produce results close to those observed in the flow experiments. The fuels tested included JP-4, hydraulic fluid, and cotton duct.

2.   Test Results

Published results (Reference 7) of extinguishing concentrations for Halons 1211, 1301, and 2402 in air and Halon 1211 in atmospheres of up to 35 percent oxygen are shown in Table 2. The fuel used was n-Heptane. It was expected that the extinguishing concentrations for halons would increase with increasing oxygen concentration. It was also expected that the relationship between the extinguishing concentrations required for the three halons would be that more Halon 1211 would be required than Halon 1301 and that more Halon 1301 would be required than Halon 2402. The experiments
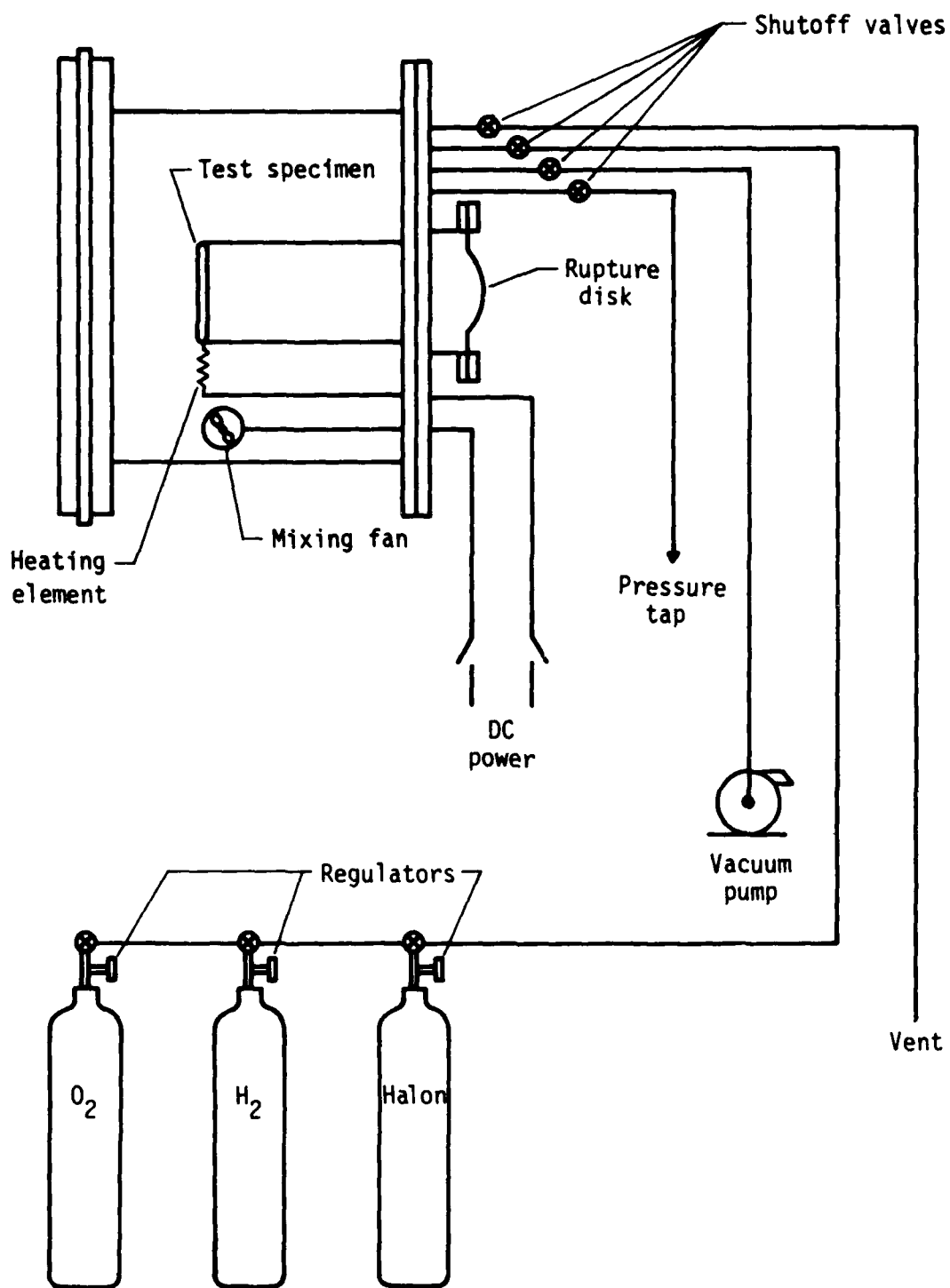
Figure 4.   Static Chamber Ignition Suppression Apparatus.

TABLE 2.   PREVIOUS FLAME-EXTINGUISHING HALON
CONCENTRATION RESULTS.[a]

Oxygen,[b] %	Halon,[c] %			Fuel
	1211	1301	2402	
21 (Air)	3.8	3.5	2.1	n-Heptane
	4.4	4.3		n-Heptane
25	7.2			n-Heptane
30	11.8			n-Heptane
35	16.0			n-Heptane

[a] Reference 7.

[b] Percent oxygen of oxygen/nitrogen atmosphere before adding halon.

[c] Percent halon of oxygen/nitrogen/halon atmosphere at flame
extinguishment.

conducted in the present tests can be expected to produce slightly different
results than those referenced caused by the lower atmospheric pressure at
Kirtland Air Force Base (AFB), New Mexico [1676 meters (5500 feet)]. The
fuels tested included n-Heptane, JP-4, Dextron II hydraulic fluid, and
cotton duct.

Table 3 lists the results of the cup burner flow tests. A
comparison of the values listed in Tables 2 and 3 shows, as was expected,
that the results obtained here for flame-extinguishing halon concentrations
were slightly lower than those published in Reference 7. Table 4 provides a
comparison of effectiveness of the three halons. The Halon 1211 and 2402
requirements are normalized to the Halon 1301 requirements for each fuel.
The Halon 1211 requirements ranged from 85 to 123 percent of the Halon 1301
required, while 67 to 84 percent of the Halon 1301 concentration was
required to extinguish the flame using Halon 2402.

Previous results for static chamber tests using Halon 1301 and a
variety of solid fuels are found in Reference 8. The published halon con-
centrations for various oxygen/helium atmosphere and cotton fuel are listed

TABLE 3. MEASURED FLAME-EXTINGUISHING HALON CONCENTRATION.

Oxygen, %	Halon, %			Fuel
	1211	1301	2402	
17.6	0.6	0.7		n-Heptane
21 (Air)	3.2	2.9		n-Heptane
		2.4	1.7	Hydraulic fluid
	2.2	2.1	1.4	JP-4
	2.0	1.9		Cotton
28.6	7.5	7.3		n-Heptane
40.0	16.5	16.5		n-Heptane
	11.6	12.2	8.8	Hydraulic fluid
	11.2	10.9	8.0	JP-4
	12.3	10.0	8.4	Cotton

TABLE 4. HALON COMPARISON FOR FLAME EXTINGUISHMENT.

Oxygen, %	Halon, % (normalized to 1301)			Fuel
	1211	1301	2402	
17.6	0.86	1.00		n-Heptane
21.0	1.10	1.00		n-Heptane
		1.00	0.71	Hydraulic fluid
	1.05	1.00	0.67	JP-4
	1.05	1.00		Cotton
28.6	1.03	1.00		n-Heptane
40.0	1.00	1.00		n-Heptane
	0.95	1.00	0.72	Hydraulic fluid
	1.03	1.00	0.73	JP-4
	1.23	1.00	0.84	Cotton

13

in Table 5. It was expected that the results obtained for Halon 1301 in oxygen/nitrogen atmospheres at Kirtland AFB, New Mexico would be close to those listed. Halon 1211 was expected to require slightly higher concentrations than Halon 1301, while Halon 2402 would require slightly lower concentrations. Limiting the total atmosphere pressure to 1.10 MPa (15 lb/in.^{2}) was expected to reduce the halon required to prevent ignition particularly at the higher oxygen concentrations.

The current results of the static chamber tests are listed in Table 6. The results showed no discernible difference between the concentration requirements of Halon 1301 and 2402. The results also showed that the concentration of Halon 1211 required was the same as or higher than the other halons. Comparison also showed that the increment in halon concentration between ignition and nonignition was, in most cases, 10 percent. Thus, the differences between the concentration of the different halons required to prevent ignition within each 10 percent increment were not distinguishable.

TABLE 5.   PREVIOUS IGNITION PREVENTION HALON
CONCENTRATION RESULTS.[a]

Oxygen, %	Halon 1301, %		Fuel
	$P_{TOT} = 15 + P_{HALON}$	$P_{TOT} = 5 + P_{HALON}$	
21 (Air)	3	2	Cotton
40	25	3	Cotton
60	45	27	Cotton
80	54	45	Cotton
100	57	49	Cotton

[a]Reference 8.

TABLE 6.   IGNITION PREVENTION HALON CONCENTRATIONS.

Oxygen, %	Halon (Ignition/nonignition), %			Fuel
	1211	1301	2402	
21	0-3	3-3.8	0-3	Cotton
	11-13	8-13	8-13	JP-4
40	30-40	30-35	30-40	Cotton
	50-60	40-50	40-50	JP-4

3.   Summary of Small-Scale Results

Two distinct types of small-scale experiments were performed to measure halon requirements for extinguishing fires. The first series of cup burner tests measured the halon concentration required to extinguish a laboratory flame. During testing with air and n-Heptane fires, CO_2 and N_2 were also tested as extinguishing agents; the percentages needed for extinguishment were 19.59 percent CO_2 and 85.6 percent total N_2 concentration as compared to 2.9 to 3.2 percent for the halons.

The second series of tests measured the halon required to prevent ignition of a fuel in premixed atmospheres. These tests were considered to represent more realistically the requirements for extinguishing deep-seated fires and preventing the spread of the fire due to persistent heat sources expected in developed fires. Previous data obtained were extended to Halon 2402 and to JP-4 fuel.

These tests evaluated the extinguishing ability of three halons on a molecular basis using laboratory fires. The concentrations required both for suppression and ignition prevention showed that Halon 2402 was molecularly superior to Halon 1211 and 1301.

B. MEDIUM-SCALE TESTING

The purpose of conducting the medium-scale fire testing was to generate information about extinguishing rates for medium-size, yet well-developed fires. The application rates and extinguishing times are used to define the extinguishing capabilities of Halon 2402 and 1211. Due to windy conditions encountered at outdoor fires, Halon 1301 was not tested. In conjunction with agent testing, delivery system parameters were evaluated. The results of that work are discussed in Section VI. Only agent capabilities will be discussed below.

1. Experimental Methods

Three types of test apparatus were used during pilot- or medium-scale testing. One apparatus consisted of a round pool of 150 ft^2 (Figure 5); the second apparatus was a running, two-dimensional (2-D) fuel fire (Figure 6); and modification of the second apparatus gave a three-dimensional (3-D) cascading fuel fire. Results of the latter two test series are also presented in Reference 9.

The 150 ft^2 pool is a concrete pit 14 feet in diameter. Before testing, a supporting water layer was added until there was a 4-inch free board. In small-scale cup burner tests, the only effect the lip height had was to reduce the burn rate. In realistic outdoor fires, lip height has other effects. If there is a wind blowing, the area behind the leading edge entrains air and alters the fire characteristics. The entrained air and fuel behind the leading edge can then act as a fire holder, making extinguishment more difficult. Also, the lip acts as a barrier to contain the heavy halon vapors. This containment results in extended inertion periods after the fire has been suppressed. With a tall lip and calm weather conditions, the inertion period can last for a extended period of time. A 150 ft^2 fire is large enough that variations in equipment and agent application can be observed while fighting a fully turbulent, radiative fire.

The design for the running fuel fire was similar to that used by Geyer at the Federal Aviation Administration (FAA) in his inclined plane studies (Reference 10). The test apparatus shown in Figure 6 is two-fifths

16

Figure 5. Pool, 150 ft^2.

the approximately 1-degree slope for a military runway, but it allowed for a consistent flow and a conservative evaluation of agents. Fuel at the top flows over a weir in order to give an even flow of fuel down the incline. The metal ramp is cooled by a water spray underneath to minimize warpage. The pan was buried in the ground for stability and ease of construction. There was no water in the lower pan, and the free board varied as the excess unburned fuel collected in the pan.

Upon completion of the testing for the running fuel fires, the apparatus was modified to include a cascading fire. The resulting apparatus shown in Figure 7 consisted of the fuel flowing over a wire and down a wire screen, then flowing down the ramp. Additional splash guards (not shown) were used to keep the fuel from splashing off the ramp and onto the ground; these splash guards were at 45-degree angles to the cascade element to minimize re-radiation effects. The purpose of the wire screen was to direct the flow of fuel while maintaining realistic airflow.

For medium-scale testing, two types of extinguishers were used. One type was a hand-held Halon 2402 extinguisher which was used in the running fuel fires. The extinguisher was a modified dry chemical extinguisher. A plain tip nozzle made of aluminum with a 0.34-inch diameter exit was used and averaged a 2.5 lb/s application rate. This application rate resulted when the extinguisher was filled with 40 pounds of Halon 2402 and charged to 200 $lb/in.^2$. All the nozzles tested are fully described in Section VI. The second extinguisher was a 150-pound wheeled unit charged to various pressures with dry nitrogen. The wheeled extinguisher was used with both Halon 1211 and 2402. During the running fuel fire, Halon 1211 was pressurized to 150 $lb/in.^2$ and discharged through two different nozzles. For the 150 ft^2 pit fires, Halon 2402 was continuously pressurized to 150 ft^2 and discharged through 5 different nozzles.

Fuel in

Drain
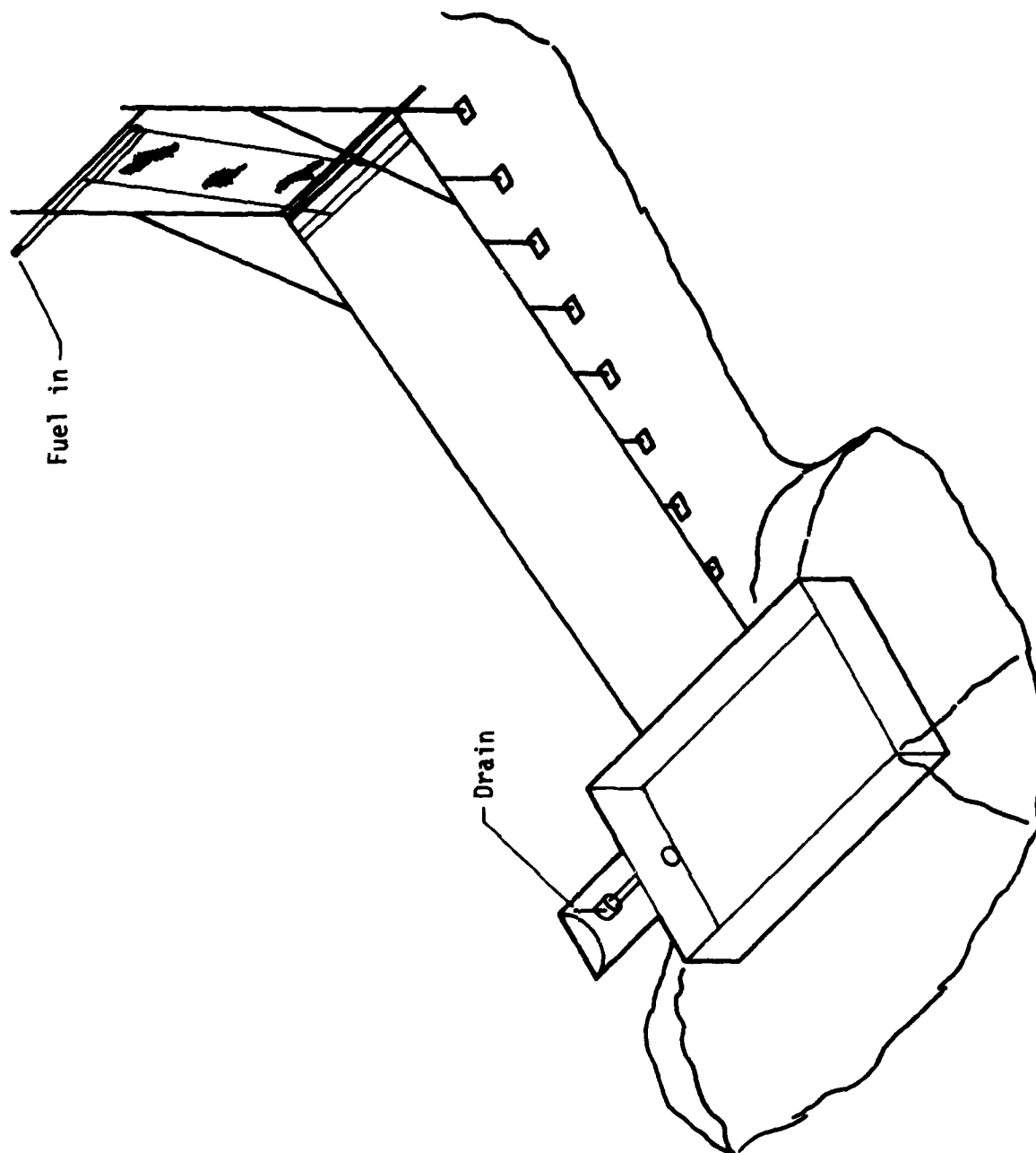
Figure 7. Cascading Fire Apparatus.

2. Test Results

a. Pool Fires

Two tests were initially run to find the specific burn rate of both JP-4 and JP-5 fuels. JP-4 burned at the rate of 0.014 lb/ft^2/s and JP-5 at 0.010 lb/ft^2/s. With a lower burn rate, the JP-5 was easier to extinguish. Most of the testing was done with JP-4 to increase accuracy of the parameters evaluated. This was done by increasing the extinguishment time caused by the increase in the degree of extinguishment difficulty. The results obtained for Halon 2402 are presented in Table 7.

TABLE 7. EXTINGUISHMENT WITH HALON 2402 IN THE 150 ft^2 FIRE PIT.

Test no.	Fuel type	Extinguishment time, s	Flow rate, lb/s	Preburn, s	Quantity fuel, gal	Nozzle, in.	Wind speed, mph	Approach
1	JP-4	150.0	0.0	N/A	50	N/A	10	None
2	JP-4	8.66	N/A	60	30	0.5	10	w/wind
3	JP-4	5.67	9.0	60	30	0.5	10	Crosswind
4	JP-5	240.0	0.0	N/A	56	N/A	5	None
5	JP-5	5.00	N/A	90	30	0.5	5	w/wind
6	JP-5	9.16	5.95	90	30	0.5	0	Crosswind
7	JP-4	15.54	N/A	60	30	0.25	0	Calm
8	JP-5	12.5	3.4	90	30	0.25	0	Calm
9	JP-4	6.8	4.2	60	30	0.328	0	Calm
10	JP-4	11.5	4.9	60	30	0.328	5	Flash back
11	JP-4	6.6	4.8	60	30	0.328	0	Calm
12	JP-4	12.6	4.8	60	30	0.328	5	Flash back
13	JP-4	14.0	5.3	60	30	0.375	5	Flash back
14	JP-4	16.0	5.3	60	30	0.375	10	Flash back

During the testing, there were no major problems encountered (Figure 8). The available extinguishment system (150-pound wheeled unit) was oversized for the fires. This resulted in higher-than-optimum agent consumption during extinguishment for these tests. The data obtained from the extinguishment systems during the medium-scale testing were used for initial designs and to prepare for large-scale testing.

Pool fire testing began with 30 gallons of JP-4 or JP-5 afloat a layer of water and then preburned for 60 seconds. For JP-5, an additional 30 seconds were added to ensure that the fire was fully established.

The fire was extinguished in every test with the most efficient extinguishment being that attained under no-wind conditions and an application rate of 4 to 5 lb/s with small droplets of Halon 2402. Even with the low energy output of this size fire, small droplets were able to completely evaporate and extinguish the fire efficiently. With larger droplets, however, there was insufficient energy in the fire to completely evaporate the droplets before passing through the flame, thereby, reducing the agent application efficiency.

In windy conditions, the small droplets had insufficient momentum to counteract the effect of the wind. This allowed the agent to draft from the fire and resulted in more flashbacks. With a larger application rate and droplet size, there was sufficient momentum to counteract the effect of the wind and extinguish the fire.

During testing, three different diameters of plain tip nozzles were tested. The smallest minimum internal diameter was 0.25 inch followed by 0.375 inch and 0.5 inch. The corresponding specific application amounts were 0.35 lb/ft^2, 0.49 lb/ft^2, 0.34 lb/ft^2, respectively. Testing with the 0.375-inch nozzle on a windy day resulted in flashbacks. The flashbacks required a higher application rate for the 0.375-inch nozzle. The other two nozzles were able to extinguish the fire and obtain similar application rates. With the long extinguishment times encountered when using the 0.25-inch nozzle, there was a noticeable increase in decomposed products generated.

Figure 8. Extinguishment of 150 ft^2 Pool.

23

In addition to the plain-tip nozzles, a water-atomizing
nozzle was tested. The nozzle had an exit diameter of 0.328 inches and an
application rate of 4.2 lb/s. In the first configuration, the nozzle had a
baffle which imparted a circular motion on the agent stream; the baffle was
removed for the modified nozzle configuration. The results showed very
little change in the agent application rate by removing the baffle. In both
cases, the nozzle sprayed agent with small droplets and a short throw range.
With the baffle, the spray angle was a 60-degree full cone; without the
baffle, a 30-degree spray angle developed. This nozzle worked very well
under calm conditions, producing a 0.2 lb/ft^2 specific application amount.
A nozzle like this would also work well for fixed systems where the nozzle
was close to the hazard or inside a structure which restricted airflow.

b. *Running Fuel Fires*

Using the apparatus shown in Figure 9, Halon 1211 and 2402
were tested for their effectiveness against a *running fuel fire*. All stud-
ies were conducted in winds of less than 10 mph. In general the agent was
applied by first approaching the pan and then attempting the extinguishment
of the ramp, an approach considered to be both realistic and representative
of a worst case scenario when only one agent is available. Criteria for
extinguishment were based on a limited amount of agent, scaled to the appa-
ratus. The results of these studies are presented in the following
paragraphs.

(1) Halon 1211

During this test set, Halon 1211 was able to extinguish
the fire 50 percent of the time. A 150-pound wheeled unit was used in all
of the tests. For testing, the storage cylinder was charged to an initial
pressure of 150 $lb/in.^2$ and two different types of water nozzles were used.
These nozzles were used because of their low flow rates. This scaled down
flow rate allowed small variations in application to become obvious. Above
5 mph, extinguishment of the fire became questionable and depended on the
type of nozzle used and the approach to the fire in relation to the wind.
Table 8 represents the results of this testing. While using a spinning

To pump

4 feet

2 feet

8 feet
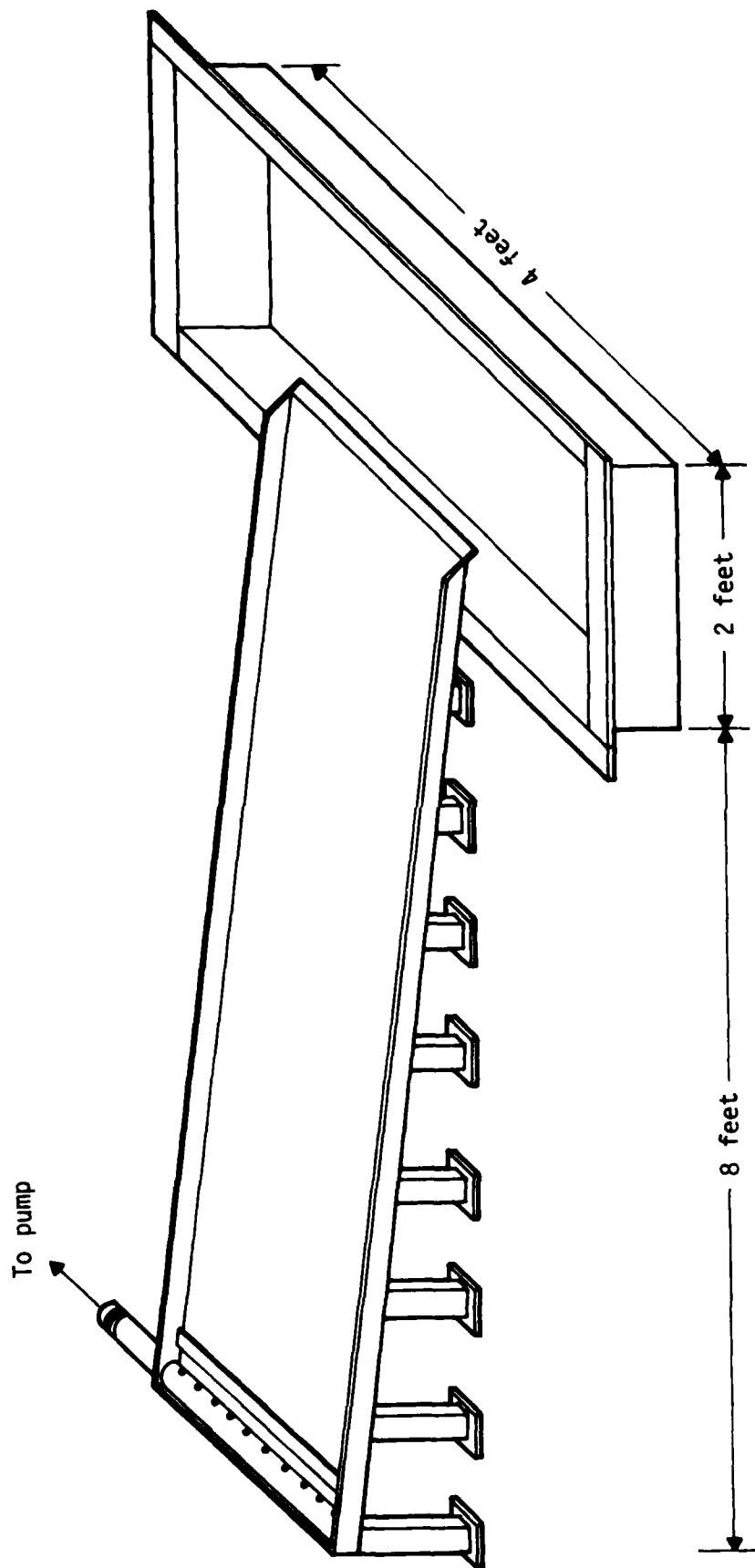
Figure 9. Running Fuel Fire Apparatus.

25

TABLE 8. HALON 1211 EFFECTIVENESS ON 2-D RUNNING FUEL FIRE.

JP-4 flow rate, gpm	Preburn time, min	Agent, lb	Extinguishment time, s	Notes
8	1	[a]129.8	60.6	b
8	1	50.6	23.7	c
8	1	[a]129	53	d
8	1	25.2	11.8	e
4	1	[a]129.8	52.4	f
4	1	27.5	13.6	g
8	2	21	10.4	h
8	2	[a]122	50.2	i
4	2	[a]119	64	j

[a]The fire was not extinguished.

[b]Spinning-tooth nozzle; tailwind caused fuel/flame to flow underneath range which caused reignition.

[c]Fixed tooth nozzle; crosswind allowed Halon 1211 cloud to form and sway across fire.

[d]Spinning-tooth nozzle; cross/headwind; fuel splashed on the ground caused reignition.

[e]Fixed-tooth nozzle; cross/headwind; attacked with the wind.

[f]Spinning-tooth nozzle; crosswind; attacked at right angle to wind.

[g]Spinning-tooth nozzle; crosswind; attacked with the wind.

[h]Fixed-tooth nozzle; crosswind; attacked with the wind.

[i]Fixed-tooth nozzle; variable wind; reignition occurred off of hot metal.

[j]Fixed-tooth nozzle; attacked with the wind towards end of extinguishment and was applied from top of ramp and then swept down ramp to the pan.

tooth nozzle, the throw range of the agent was substantially reduced. This nozzle used during winds above 5 mph resulted in nonextinguishment of the fire in most cases. While using a fixed-tooth nozzle, the fire was easily extinguished even with winds up to 10 mph. Both of the water nozzles resulted in reduced throw rates but allowed for a reduced application rate for agent scaling. Halon 1211 was tested for comparison data and to familiarize the firefighter with the test apparatus.

(2) Halon 1202

Halon 2402 (Table 9) extinguished the fire in all cases, both in windy (>5 mph) and calm conditions. The Halon 2402 was containerized in a 40-pound, hand-held unit pressurized to 200 lb/in.^{2} with a 2.5 lb/s plain tip nozzle. Variations in agent application rate occurred during testing as a result of hand-held valve operation. Success of Halon 2402 is partially due to its ability to temporarily inert the fuel, thereby decreasing flashbacks. When using the fixed-tooth nozzle, both Halon 1211 and 2402 were able to extinguish the running fuel fire; and during testing, less Halon 2402 was required overall (18 pounds average for the Halon 2402 versus 25 pounds average for Halon 1211). In addition, Halon 2402 is not as dependent on the technique used during application.

(3) Combination Agent Halon 1211 and Halon 2402

A combination of Halon 1211 and Halon 2402 was used for extinguishment to accomplish three objectives: (1) to reduce the cost of agent used; (2) to reduce the toxicity of Halon 2402; and (3) to improve the three-dimensionality of the Halon 2402 by adding a more gaseous agent while retaining the same firefighting characteristics.

The data shown in Table 10 points to a decreasing effectiveness for Halon 1211 concentration of 50 percent or above. This is because the agent becomes more susceptible to the effects of wind as the percentage of the more gaseous Halon 1211 increases. The 75-percent Halon 2402/25-percent Halon 1211 mixture showed improved performance over pure Halon 2402. The combination agent was contained in a 40-pound, hand-held extinguisher pressurized to 200 lb/in.^{2} and applied through a 2.5 lb/s plain

27

TABLE 9. HALON 2402 EFFECTIVENESS ON 2-D RUNNING FUEL FIRE.

JP-4 flow rate, gpm	Preburn time, min	Agent, lb	Extinguishment time, s	Notes
8	1	17.5	9	a
8	1	17.25	7.2	b
8	1	16	4.0	c
4	1	11.25	4.4	d
4	1	10.3	5.5	e
8	2	29.5	12.1	f
8	2	43	19.0	g
8	2	11	4.8	h
4	2	14.5	6.4	i
4	2	11.5	4.3	j

[a]Tailwind caused ignited fuel to flow under ramp; reignition was controlled.

[b]Head-crosswind; attacked at right angle to the wind.

[c]Head-crosswind; attacked at right angle to the wind.

[d]Tailwind; reignition from ignited fuel under ramp was controlled.

[e]Tailwind; reignition from ignited fuel under ramp was controlled.

[f]Head-crosswind; initial attack was at right angle to wind then moved to apply agent with wind.

[g]Head-crosswind; attacked at right angle to wind; flashback occurred off of concrete adjacent to test apparatus. Valve on extinguisher stuck in open position.

[h]Crosswind; attacked with the wind.

[i]Crosswind; attacked at right angle to the wind.

[j]Crosswind; attacked at right angle to the wind.

TABLE 10. COMBINATION AGENT HALON 1211/HALON 2402 EFFECTIVENESS ON
2-D Running Fuel Fire.[a]

JP-4 flow rate, gpm	Agent, lb	Extinguishment time, s	Notes
25% 2402/75% 1211			
8	20.5	11	c
8	[b]43.25	34	d
4	[b]40.25	30	e
4	12.5	6	f
50% 2402/50% 1211			
8	31	22	g
8	[b]42.5	29	h
4	11.5	8	i
4	10.5	7	j
75% 2402/25% 1211			
8	15.5	5	k
8	11	3.5	l
4	18	6	m
4	16.25	6	n

[a]One-minute preburn.

[b]Fire was not extinguished.

[c]Calm winds.

[d]Head-crosswind; attacked at right angle to wind; agent unable to overcome drafting effects of wind.

[e]Headwind; attacked at right angle to wind; agent unable to overcome drafting effects of wind.

[f]Head-crosswind (not as strong as d); attacked at 45-degree angle to wind.

[g]Crosswind; attacked at 45-degree angle to wind.

[h]Tailwind fire; under ramp caused reignition.

[i]Crosswind; attacked at right angle to wind.

[j]Tailwind; reignition caused by fire under ramp was controlled.

[k]Slight head-crosswind; attacked at 45-degree angle to wind; excess agent applied because of visibility impairment caused by the halon cloud.

[l]Slight headwind; attacked into wind.

[m]Headwind; attacked at 45-degree angle to wind.

[n]Head-crosswind; attacked at 45-degree angle to wind.

tip aluminum nozzle (length = 3 inches, exit diameter = 0.34 inches). With an increased liquid component, the blended agent (75-percent Halon 2402/25-percent Halon 1211) yields better throw and flame-penetrating ability than other halon combinations for this type fire.

An advantage gained by adding a vaporizing agent like Halon 1211 is that Halon 1211 breaks up the stream evenly and reduces the droplet size. This allows the agent to completely evaporate and interact with the fire. This combination is very effective with hand-held extinguishers which are pressurized with a fixed charge. With pure Halon 2402, the droplet size grows as the pressure drops. Halon 1211, with its higher vapor pressure in the blended agent, continues to keep the droplet size small, even as the pressure drops. There was another problem encountered during this test which accounted for some of the fires not being extinguished. As the percentage of Halon 1211 decreases, the fill ratio in a cylinder filled by weight decreases because the density of Halon 1211 is less than that of Halon 2402. With a lower fill ratio, the exit pressure at the nozzle is higher resulting in higher application rates. This can be seen by looking at the data in Table 10. As the percentage of Halon 1211 decreases, the application rate increases. When looking at the amount of agent used for this size fire, the mixture with 25 percent Halon 1211 yielded comparable and in some cases better results than Halon 2402 only.

c. Cascading Fuel Fire

Upon completion of the studies for a running fuel fire, the apparatus was modified to assess cascading fire characteristics (Reference 11). Tests were continued against the modified apparatus which included a cascading fuel element. The criteria for extinguishment were based on a limited amount of agent scaled to the apparatus. The results of these studies are presented in the following paragraphs.

(1) Halon 2402

Halon 2402 extinguished the fire in every case (Table 11). The ability of 2402 to combat a cascading fuel fire is enhanced because of its temporary inerting ability. The agent was discharged from a

TABLE 11. EFFECTIVENESS OF HALON 2402 ON CASCADING FUEL FIRE.

JP-4 flow rate, gpm	Agent, lb	Extinguishment time, s	Notes
7.0	36	7	a
2.8	74.5	13	b

[a]Tailwind; attacked with wind; ignited fuel under ramp was controlled.

[b]Cross-headwind; attacked at right angle to wind; reignition occurred off of hot metal.

10-gallon wheeled unit with 150 lb/in.^{2} of continuous pressure. The nozzle used was a plain tip brass nozzle (length = 4.75 inches, exit diameter = 0.5 inches).

(2) Combination Halons

The combination agent Halon 1211/Halon 2402 (25 percent/ 75 percent) developed in the running fuel fire study was evaluated on the cascading apparatus (Table 12). The performance of this agent, considering extinguishment time and amount of agent used, was less efficient than using Halon 2402 only against the cascading fire. This reduction in efficiency is probably caused by the increased buoyancy of the cascading fire. This makes the gaseous aspect of the blended agent more of a liability. With the increased energy available in the cascading fire, larger droplets could be used to better penetrate the flame front.

3. Summary of Agent Concepts

The following general concepts for Halon 2402 were developed as a result of the evaluation of agent effectiveness against medium-scale fires.

TABLE 12. EFFECTIVENESS OF 75 PERCENT HALON 2402/25 PERCENT HALON 1211
          COMBINATION AGENT ON CASCADING FUEL FIRE.

JP-4 flow rate, gpm	Agent, lb	Extinguishment time, s	Notes
2.8	84.6	15	a
7.0	123.5	14	b
2.8	32.0	5	c

[a] Calm wind; reignition occurred off of hot metal.

[b] Crosswind; fire on ground caused by splashing fuel was controlled.

[c] Crosswind; attacked at right angle to wind.

The ability of an agent to inert the fuel is essential to its firefighting ability. If there is a constant new source of fuel and if there is no inertion ability, flashback occurs from ignition sources such as hot metal or as the agent is directed towards other parts of the fires.

An agent applied from the top of the ramp and allowed to flow with the fuel is more effective due to the flame structure, which is less developed at the fuel source and develops as the fuel flows down the pan.

Halon 1211, although quite effective in quiescent conditions, is not as effective as Halon 2402 for some fire scenarios in a windy environment.

Halon 2402 is reliably effective in the extinguishment of a cascading fuel fire (Figure 10), partially becaue of its ability to temporarily inert the fuel surface.

The addition of 25 percent Halon 1211 to Halon 2402 increases effectiveness of Halon 2402 for running fuel fires but decreases its effectiveness against cascading fires in windy conditions.

Further work using the cascading apparatus has been accomplished at NMERI (Reference 9). This extended work included cascading fire characterization and burn rate studies.
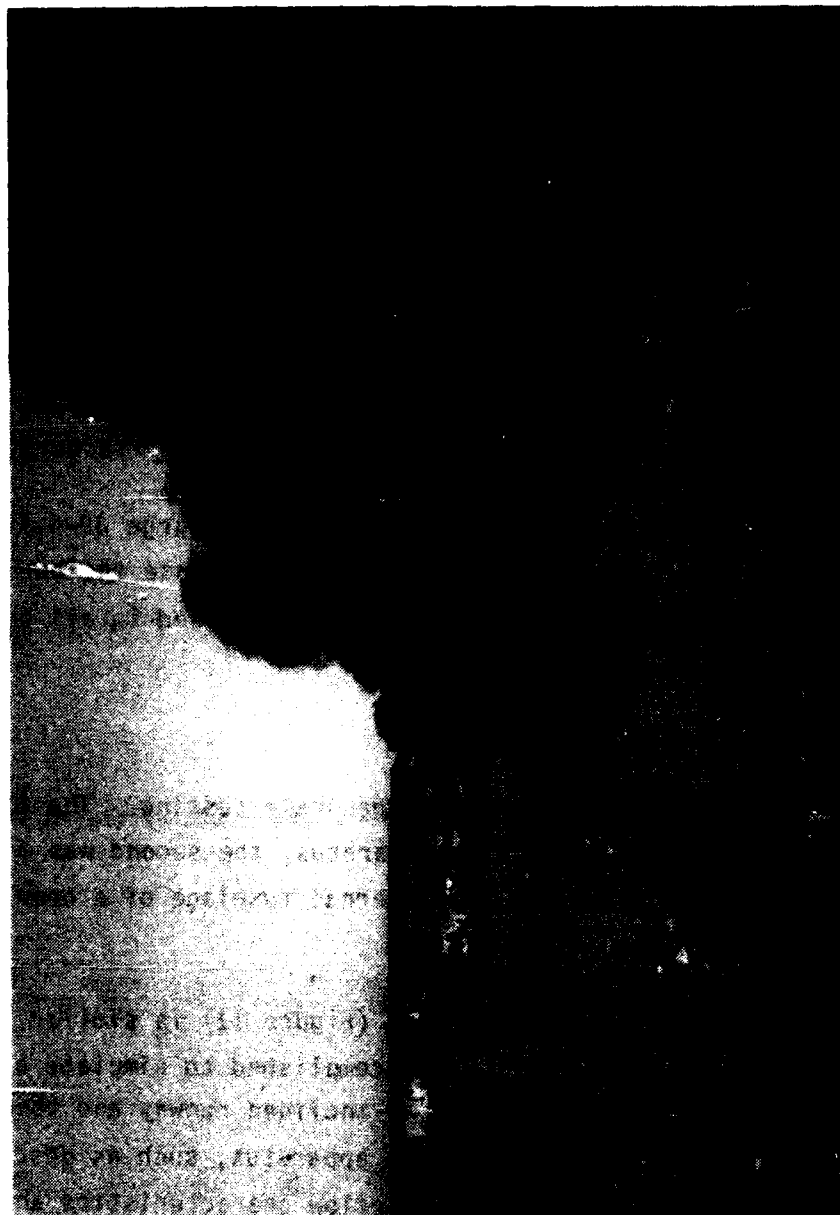
Figure 10. Cascading Fuel Fire.

C. LARGE-SCALE TESTING

Large-scale testing with realistic fires expands the information already gathered and finalizes the fire performance data. By working with realistic fire scenarios, performance information on near optimum applications of Halon 2402 was acquired. An overall picture of how Halon 2402 performs on large fires is presented below.

In large fires, there are many factors which interact and control the situation. These factors include the application technique of the fire-fighting agent, the training level of each firefighter, and the intensity change because of the mental attitude the firefighter has each day. The human factor is the hardest to control. Every firefighter will perceive a fire situation differently. Other factors involved include the equipment condition, agent-fill ratio, operating cylinder pressure, nozzle type, wind direction, fuel loading, amount of debris, and other secondary factors.

This section will discuss how well halons extinguish large JP-4 fires. JP-4 was used in all of the large-scale test fires to increase the burn rate and difficulty of suppression. The same firefighter was used in all of these tests to control the human factor.

1. Experimental Methods

Three apparatus were used during large-scale testing. The first was a 124 ft^2 three-dimensional (3-D) fire apparatus, the second was a 2,200 ft^2 pool fire, and the third was the internal fuselage of a complete C-131 aircraft.

The design of the 3-D test apparatus (Figure 11) is similar to the medium-scale cascading fuel fire. This was accomplished to simulate a post-crash scenario where fuel is cascading onto an inclined runway and then pooling elsewhere. It was felt that a cascade apparatus, such as described in Reference 12, would not allow the proper airflow characteristics and would give the agent a backboard to rebound. Since the performance of fire-fighting agents is dependent on these variables, it was determined that such

34
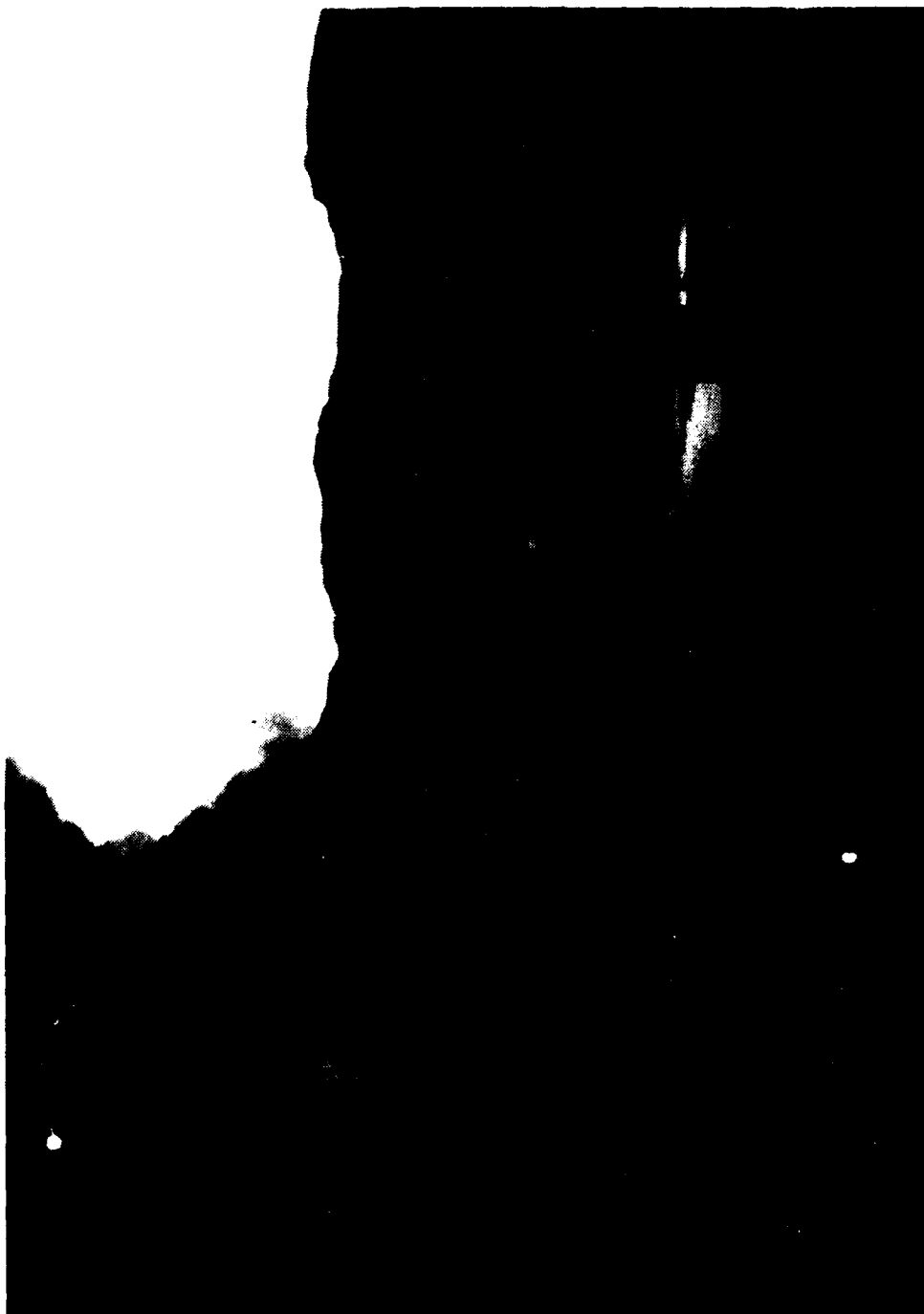
Figure 11. Large-Scale 3-D Apparatus.

an apparatus would not give practical baseline results regarding agent capabilities. For testing, fuel was pumped at a rate of 25 gallons per minute. Fuel was spread over a 24-inch manifold and cascaded to a lower pan, a 40-inch drop. A metal screen directed the fuel between the upper and lower parts of the apparatus. This reduced splashing and spread the fuel out. The lower ramp was 16 ft^2, set at 5 degrees from horizontal. A 12-inch lip set at 45 degrees surrounded the upper part of the ramp to reduce splashing. After the fuel had flowed down the ramp, it dropped 6 inches into the 150 ft^2 concrete pool already described in medium-scale testing. The apparatus was constructed and supported so no cooling was needed, resulting in a realistic fire situation.

Two areas were used for the 2200 ft^2 pool fires. Information on the size of a pool fire which could be extinguished with a single hand line was sought during this testing. The first area used for testing was the Kirtland AFB Fire Department training pits (Figure 12). An 80-foot diameter burn area was surrounded by a berm with a large approach area. Inside of the pit was an aircraft mockup which divided the pool into two areas. The second burn area was a continuous pool, without any objects, approximately 50 by 50 feet. After rounding off the corners, the pool had a total area of 2200 ft^2. Eight-inch berms continued the water and fuel (Figure 13.)

The final large-scale test was conducted inside a C-131 aircraft (Figure 14). This work was done to examine a drafty fire scenario inside an aircraft. More detailed studies performed inside the C-131 can be found in Reference 6.

2. Test Results for 3-D Fire Suppression

The results generated from the 3-D testing are presented in Table 13. The burn rate for the 150 ft^2 pool was 2.1 lb/s. By adding the 3-D apparatus, the burn rate increased to 3.8 lb/s. With an increase of only 24 ft^2 (14 percent), the burn rate was increased by 45 percent. This showed how significantly the configuration affected the intensity of the fire.

Figure 12. Kirtland AFB Fire Department Training Pits.

Figure 13. Pool, 2200 ft^2.
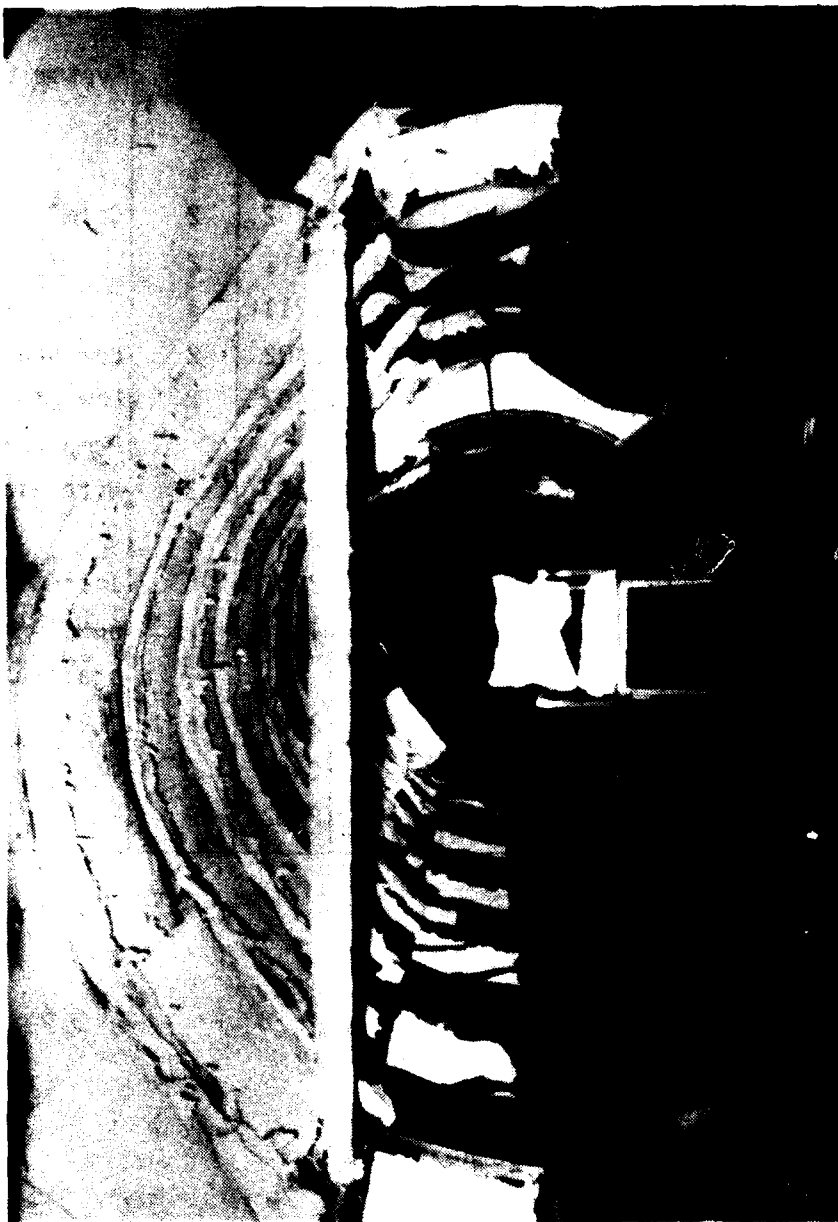
Figure 14.   Interior of C-131 Aircraft.

TABLE 13. 3-D FIRE PIT RESULTS.

Test no.	Pre-burn, s	Fuel-burn, s	Fuel-burn, gal	Post-burn, s	Ext. time, s	Agent application, s	Agent application, lb	Halon agent	Nozzle type[a]	Notes
1		30	11.5	95						System test
2	35	90	33.6		None	38	187	2402	0	
3	30	140	42.8	55	None	26	129	2402	1	
4	30	90	33.5	None	19	19	164	2402	2	Calm
5	35	118	35.7	50	None	48	142	1211	2	
6	30	164	47.4	110	None	90	350	1211	1	
7	35	115	33	20	None	35	298	2402	2	Low pressure
8	35	95	35.7	45	None	41	280	2402	2	Low pressure
9										Pump failure
10	30	45	31.2	None	26	26	145	2402	3	With wind
11	30	95	35	55	None	46	193	2402	4	
12	25	107	47.3	115	None	47	181	2402	5	Increased fuel pump pressure against wind
13	28	95	44.5	45	None	35	180	2402	6	
14	28	91	59.1	None	25	25	192	2402	2	
15	30	80	39.0	None	19	19	169	2402	7	

[a]Nozzle specification

    0 Modified water atomizing nozzle

    1 Standard Air Force P-13 nozzle

    2 0.5-inch converging pipe nozzle

    3 0.375-inch converging pipe nozzle

    4 0.25-inch converging pipe nozzle

    5 0.25-inch converging/diverging nozzle

    6 0.315-inch converging/diverging nozzle

    7 0.50-inch modified Air Force nozzle

For converging nozzles, dimensions are for the minimum diameter.

Extinguishment of a fire is very difficult when fresh fuel is continuously being supplied. Testing showed two ways to extinguish this fire. The easiest way was to form a cloud of halon and have it engulf the cascading portion of the apparatus after the pool and ramp have been extinguished. The other way was to extinguish and temporarily inert the fuel surface flowing down the wire screen (Figure 15). This allowed unburned fuel to pour down the screen which reduced the burn rate. To complete extinguishment, the rest of the fire needed to be suppressed before the fuel on the screen could reignite.

Wind direction was also important in extinguishment. To simulate a worst-case scenario, the 3-D apparatus was approached from the front side, where the firefighter had the 150 ft^2 pool between him and the 3-D fire (Figure 16). In all of the tests with Halon 2402, the pool fire was easily extinguished and the 3-D apparatus was quickly attacked. When fighting the fire with Halon 1211, the firefighter had a difficult time in keeping the pool fire extinguished. Halon 2402 greatly reduced flashback from the 3-D apparatus to the pool. When the wind was with the firefighter (blowing from the firefighter to the 3-D apparatus), extinguishment was easier to obtain. The wind helped draft the agent into the fire and reduced flashback into the pool.

Eight nozzles (described in Table 13) were tested at the cascading 3-D fire apparatus. Three of the nozzles were able to extinguish the fires. Two of the nozzles had an internal orifice of 0.5 inches and one had a 0.375-inch orifice. The 0.375-inch miminum internal diameter nozzle had a flow rate of 5.6 lb/s and a specific application amount of 0.833 lb/ft^2. The specific application amount was obtained by dividing the weight of the agent used during extinguishment by the burning area (174 ft^2). When using the 0.375-inch nozzle, the fire was extinguished because of a 5 mph wind which was with the firefighter. Using a 0.5-inch minimum internal diameter plain tip nozzle resulted in a specific application amount of 1.10 lb/ft^2, which was effective in all types of windy conditions.

a.   3-D Test 1

This was the system checkout. The pump supplied 75 pounds of JP-4 in 30 seconds. All parts of the system worked without a problem. The system was ready for testing.

Figure 15. Extinguishment of Large-Scale 3-D Fires.
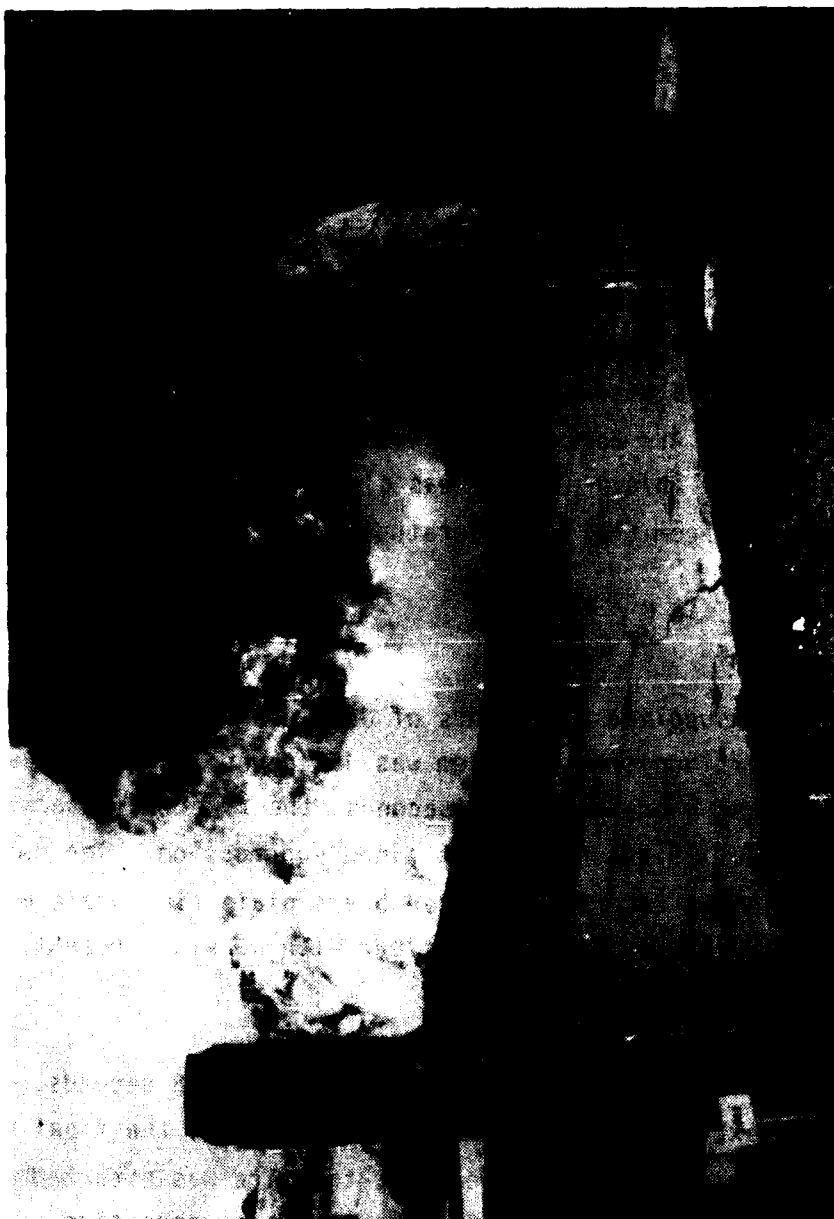
Figure 16. Placement of Firefighter and 3-D Apparatus.

b. 3-D Test 2

The pump supplied 218 pounds of JP-4 over 90 seconds. The initial weight of the extinguishment system was 467 pounds; the final weight was 280.5 pounds. After a preburn of 35 seconds, the fire was attacked with Halon 2402 for a total of 37.5 seconds without obtaining suppression. The nozzle used was a modified spray system water nozzle (1HD) with an exit diameter of 0.328 inches and an application rate of 4.97 lb/s. The sky was clear with a 15 to 20 mph crosswind. The postburn was 55 seconds.

c. 3-D Test 3

The pump supplied 278 pounds of JP-4 over 140 seconds. The initial weight of the extinguishment system was 581 pounds; the final weight was 452 pounds. After a preburn of 30 seconds, the fire was attacked with Halon 2402 for a total of 26 seconds without obtaining suppression. The nozzle used was a standard Air Force nozzle with an orifice of 0.27 inches and an application rate of 4.9 lb/s. The sky was clear with a 6 mph wind against the firefighter (blowing from the 3-D apparatus to the firefighter). The postburn was 55 seconds.

d. 3-D Test 4

The pump supplied 218 pounds of JP-4 over 90 seconds. The initial weight of the extinguishment system was 451 pounds; the final weight was 287.5 pounds. After a preburn of 30 seconds, the fire was attacked with Halon 2402 for a total of 19 seconds and obtained suppression. The nozzle used was a 0.5-inch minimum internal diameter brass plain tip nozzle with an application rate of 8.9 lb/s. The sky was clear with no wind present.

e. 3-D Test 5

The pump supplied 232 pounds of JP-4 over 118 seconds. The initial weight of the extinguishment system was 411 pounds; the final weight was 269 pounds. After a preburn of 35 seconds, the fire was attacked with Halon 1211 for a period of 45 seconds without obtaining suppression. The

nozzle used was a 0.5-inch minimum internal diameter brass plain tip nozzle with an application rate of 4.0 lb/s. The sky was partially cloudy with a 5 to 10 mph crosswind. The postburn was 50 seconds.

f.   3-D Test 6

The pump supplied 308 pounds of JP-4 over 164 seconds. The initial weight of the extinguishing agent was 350 pounds; the final weight was 0 pounds. After a preburn of 30 seconds, the fire was attacked with Halon 1211 for a total of 90 seconds without obtaining suppression. The nozzle used was a standard Air Force halon nozzle with an orifice of 0.27 inches and an application rate of 4.4 lb/s. The sky was cloudy with a 20 to 25 mph wind with the firefighter. The postburn was 70 seconds.

g.   3-D Test 7

The pump supplied 215 pounds of JP-4 over 115 seconds. The initial weight of the extinguishing system was 579 pounds; the final weight was 281 pounds. After a preburn of 35 seconds, the fire was attacked with Halon 2402 for a total of 35 seconds without obtaining suppression. The nozzle used was a 0.5-inch minimum internal diameter brass plain tip nozzle with an application rate of 8.5 lb/s. The sky was cloudy with a 20 to 25 mph wind with the firefighter. The postburn was 20 seconds. The supply pressure to agent cylinder was low, resulting in reduced flow rate and throw range.

h.   3-D Test 8

The pump supplied 232 pounds of JP-4 over 95 seconds. The initial weight of the extinguishing system was 563 pounds; the final weight was 283 pounds. After a preburn of 35 seconds, the fire was attacked with Halon 2402 for a total of 41 seconds without obtaining suppression. The nozzle used was 0.5-inch minimum internal diameter brass plain tip nozzle with an application rate of 6.8 lb/s. The sky was partly cloudy with a 12 to 14 mph wind. The postburn was 45 seconds.

In Tests 7 and 8, the agent flow rates were low because of a pressurizing problem with the extinguisher system.

i. 3-D Test 9

The pump failed part way through the test with no results.

j. 3-D Test 10

The pump supplied 203 pounds of JP-4 over 45 seconds. The initial weight of the extinguishing system was 468 pounds; the final weight was 323 pounds. After a preburn of 30 seconds, the fire was attacked with Halon 2402 for a total of 25.6 seconds and to obtain suppression. The nozzle used was a 0.375-inch minimum internal diameter brass plain tip nozzle with an application rate of 5.7 lb/s. The sky was partially cloudy with no wind.

k. 3-D Test 11

The pump supplied 228 pounds of JP-4 over 113 seconds. The initial weight of the extinguishing system was 471 pounds; the final weight was 323 pounds. After a preburn of 30 seconds, the fire was attacked with Halon 2402 for a total of 46 seconds without obtaining suppression. The nozzle used was a 0.25-inch minimum internal diameter brass plain tip nozzle with an application rate of 4.2 lb/s. The sky was cloudy with a 10 mph wind against the firefighter. The postburn was 55 seconds.

l. 3-D Test 12

The pump supplied 307 pounds of JP-4 over 127 seconds. The initial weight of the extinguishing system was 468 pounds; the final weight was 287 pounds. After a preburn of 25 seconds, the fire was attacked with Halon 2402 for a total of 46 seconds without obtaining suppression. The nozzle used was 0.25-inch minimum internal diameter brass plain tip nozzle with a diverging exit and an application rate of 4.1 lb/s. The sky was partly cloudy with a 3 to 5 mph crosswind. The postburn was 75 seconds.

m.   3-D Test 13

The pump supplied 289 pounds of JP-4 over 104 seconds. The initial weight of the extinguishing system was 467 pounds; the final weight was 287 pounds. After a preburn of 28 seconds, the fire was attacked with Halon 2402 for a total of 35 seconds without obtaining suppression. The nozzle used was a 0.3125-inch minimum internal diameter brass plain tip nozzle with a diverging exit and an application rate of 5.1 lb/s. The sky was clear with a 6 to 8 mph wind with the firefighter. The postburn was 45 seconds.

n.   3-D Test 14

The pump supplied 384 pounds of JP-4 over 122 seconds. The initial weight of the extinguishing system was 476 pounds; the final weight was 284 pounds. After a preburn of 28 seconds, the fire was attacked with Halon 2402 for a total of 25 seconds to obtain suppression. The nozzle used was a 0.5-inch minimum internal diameter brass plain tip nozzle with an application rate of 7.7 lb/s. The sky was clear with a 4 to 5 mph wind against the firefighter.

o.   3-D Test 15

The pump supplied 254 pounds of JP-4 over 80 seconds. The initial weight of the extinguishing system was 434 pounds; the final weight was 265 pounds. After a preburn of 30 seconds, the fire was attacked with Halon 2402 for a total of 19 seconds to obtain suppression. The nozzle used was a modified P-13 Air Force halon nozzle with an orifice of 0.5 inch and an application rate of 9.2 lb/s.

The extinguisher used in all of these tests was a wheeled unit manufactured by Fire Guard (Model FEU 1/m). During all of the tests, there was a constant nitrogen charge of 150 lb/in.^{2} gage flowing. In Tests 1 through 14, a 0.75-inch internal diameter fire hose was used; and in the final test, a 1-inch internal diameter fire hose was used.

3. Test Results for 2200 ft^2 Fire Suppression

Three fires were conducted at the Kirtland AFB Fire Department training pits. Base fire personnel were used for this testing. Chemical gas sampling information was gathered during the fire. Also inspected was the reaction of personnel who used the agent and how the agent performed. Additional tests were performed in a continuous pool. Pictures of each test setup are shown in Figures 17 and 18.

Grab samples were taken of the fire products during extinguishment of each test fire. A 4-inch stainless steel tube, supported by a steel frame (Figure 19), had gas samples pumped through it past a sampling area. Solenoids were opened at different intervals, and a grab sample of fire products flowing through the tube was taken. During each extinguishment, the backup firefighter also took a grab sample of the air by the head of the firefighter using the nozzle. The results of this study are discussed further in Section IV.

Before testing started, the ground in the fire pit was sprayed with water to minimize fuel migration into the ground. Without a continuous layer of water, the fuel did not spread evenly. The resultant JP-4 fire was a series of separate pool fires feeding into a single cloud (Figure 20). At first, this did not seem to be a problem because an intense fire was generated. However, during extinguishment there were no flashbacks. Each pool was separated from the other pools; therefore, once it was extinguished, the pool would not reignite. Without having to worry about the fire flashing back, it was only a matter of time until the fire was extinguished. The wind speed during extinguishment was 1 to 2 mph. For all of the fires, there was a 5-second preburn. The preburn period started after the whole area was ignited. This preburn period was chosen because of the fuel loading and pool area.

During the first fire test, the fire was attacked with Halon 1211. For 5 seconds after the whole area was burning, 150 to 200 gallons of JP-4 jet fuel were preburned. A total of 500 pounds of agent were used without extinguishing the fire. After suppressing the fire close to the nozzle, the agent did not have sufficient throw range to extinguish more of the fire. The firefighters had no problem using the 1211 as efficiently as possible. Some agent

48

Figure 17. Fire Area at Training Pits.
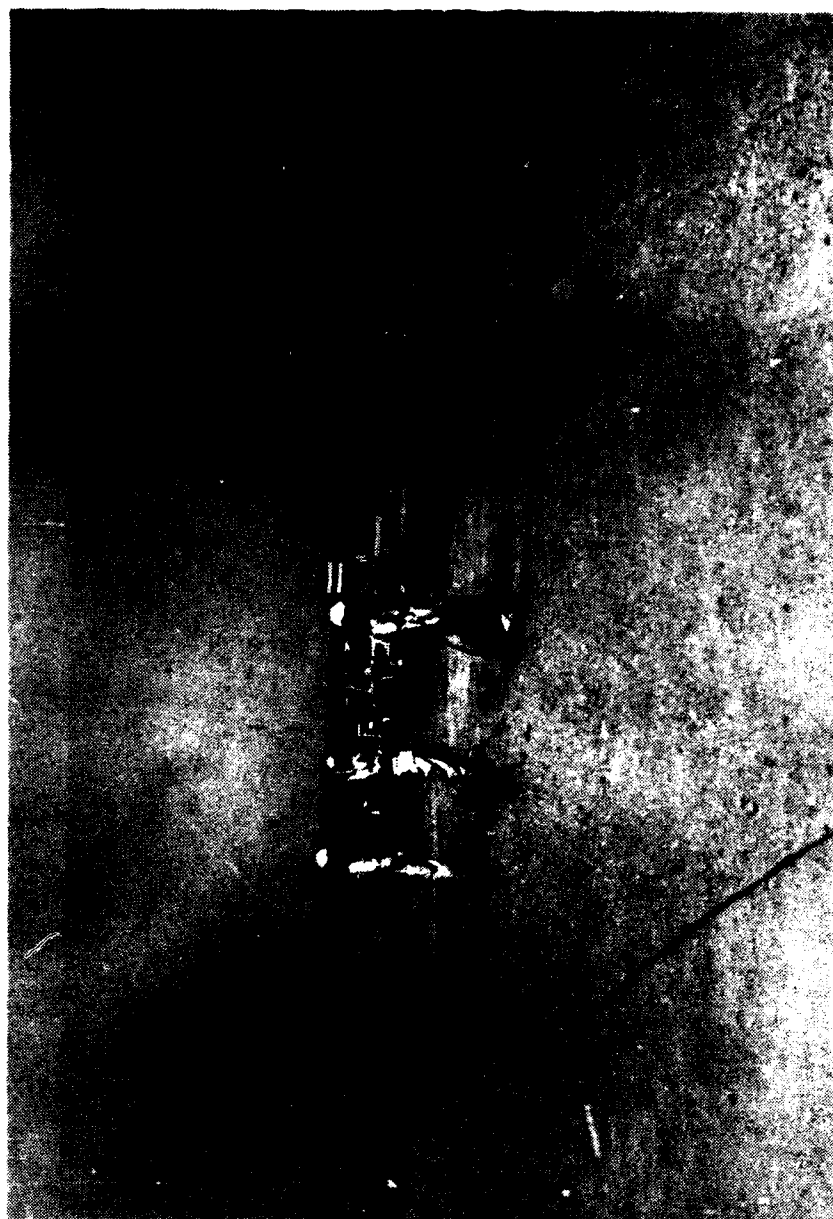
Figure 18. Test Setup for 2200 ft^2 Pool.
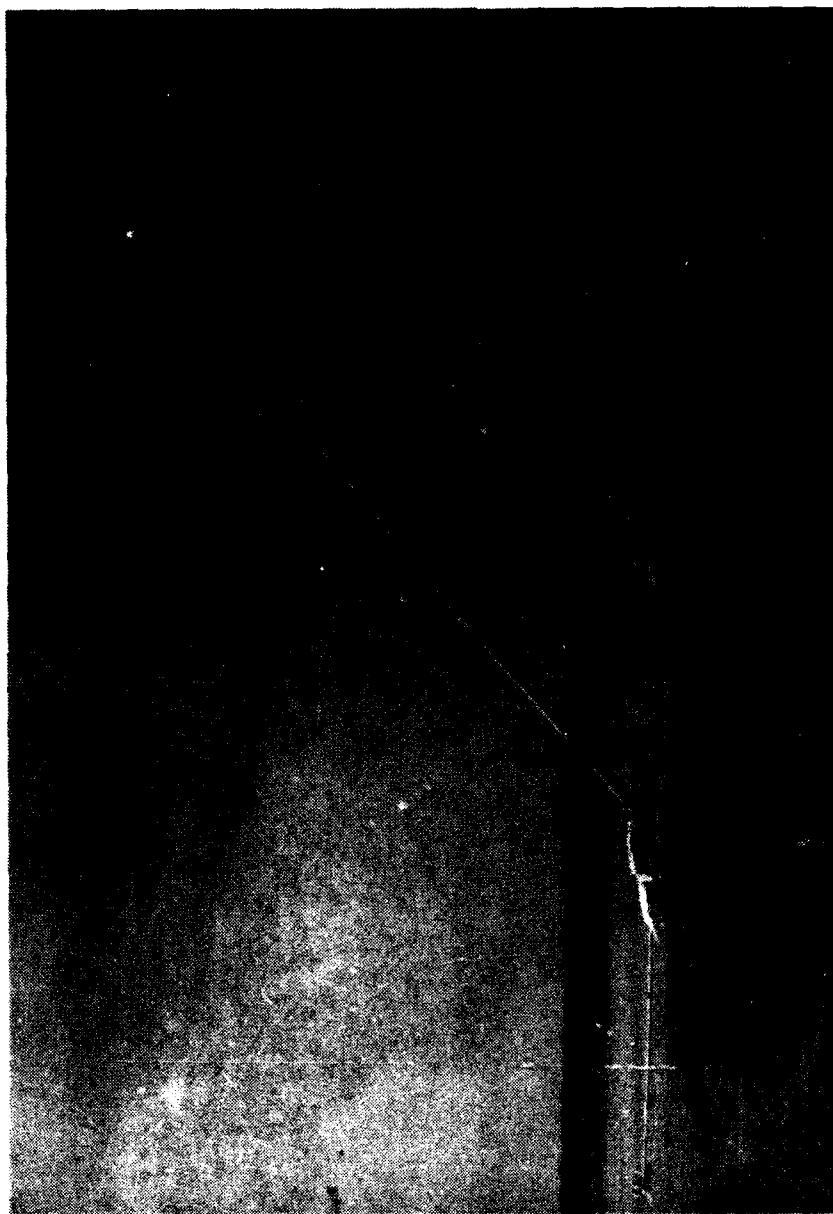
Figure 19. Gas Sampling Tube for Large-Scale Pit Fires.
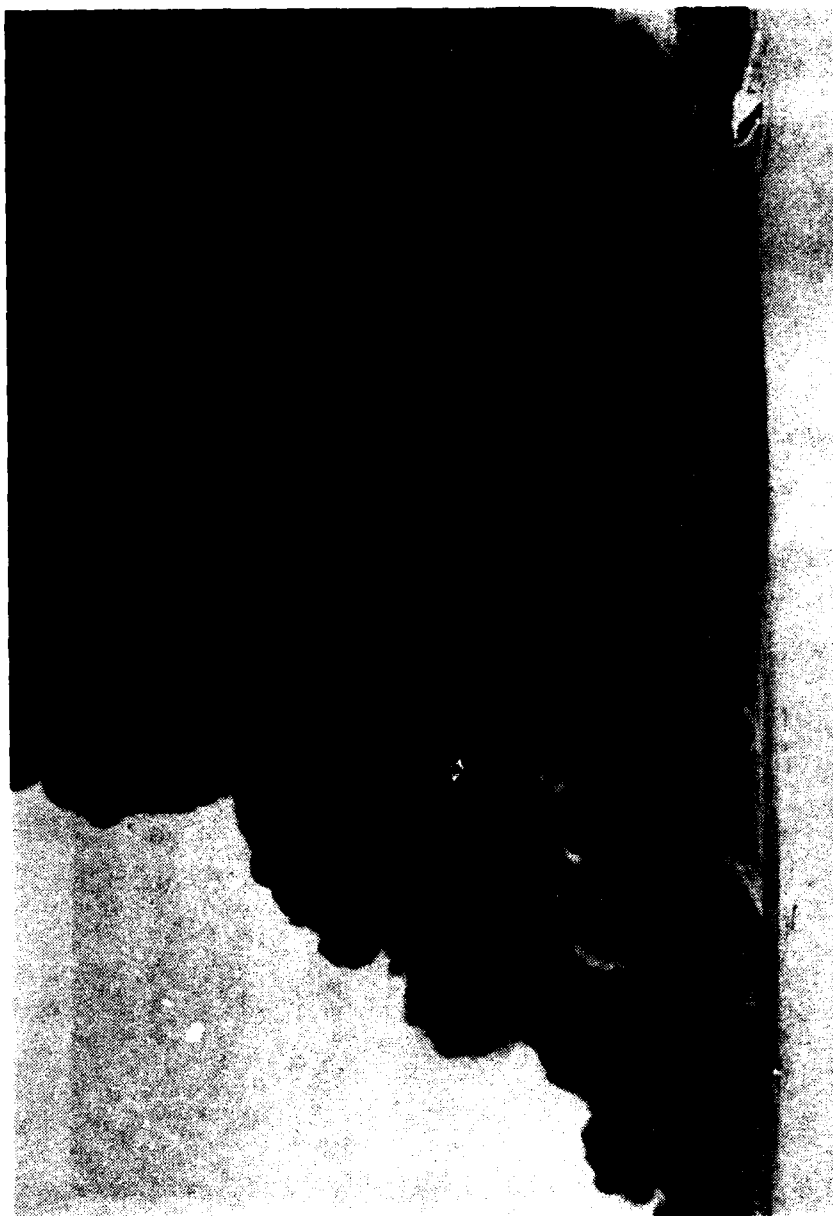
Figure 20.   Large-Scale Pool Fire in Training Pits.

was wasted as the firefighter moved from one side of the aircraft mockup to the other side. There was no flashback, and approximately 60 percent of the fire was suppressed.

Halon 2402 was used for the second test. The modified Air Force P-13 nozzle with a 0.5-inch orifice was used. A 100-foot fire hose with a 1-inch internal diameter was used. During discharge, 440 pounds of Halon 2402 were charged to an initial pressure of 200 lb/in.^{2} and a flowing pressure of 180 lb/in.^{2}. After the whole pit was ignited, 150 gallons of JP-4 jet fuel was preburned for 5 seconds. The agent was easily able to extinguish the fire within range. While transferring the hose from one side to the other, the firefighter did not completely shut off the agent flow and a large amount of agent was lost. Before the agent supply was depleted, 90 percent of the fire was extinguished. The firefighters used the agent as if it were Halon 1211, which vaporizes readily. The firefighters had been instructed to spread it thin and keep moving the nozzle. During the fire neither happened. This indicated that some retraining of the firefighters would be necessary when introducing Halon 2402 into the military. Because of the erratic use of the Halon 2402, a flow rate for the agent was not obtained.

The final test at the training pits was conducted with Halon 2402 and the modified Air Force nozzle which had been drilled out to 0.5-inches. Approximately 300 gallons of JP-4 were fed into the fire pit area and ignited. After a 5-second preburn, the fire was attacked (Figure 21). The firefighters, who had been trained with Halon 1211 and instructed about Halon 2402, changed to a different nozzleman before every test. This resulted in no increase of experience at the nozzle. During extinguishment, the first 25 percent of the fire was easily suppressed and quickly extinguished. The firefighter then moved to the right side of the mock aircraft and quickly inerted it. After that, communication broke down; the firefighter did not move to the left side of the mockup but continued to fight the fire on the right side. This was very inefficient because the mockup was blocking the agent and the wind was blowing from the left to the right and moved the agent away from the fire. After trying with little success, the firefighter started to move to the left side but ran out of agent before reaching it. A total of 70 percent of the fire was extinguished.

Figure 21. Extinguishment of Large-Scale Pit Fire With Modified
Air Force Halon Nozzle.

54

Because of all the inconsistencies in the fires, the extinguishing data was valuable only as comparative information. The gas samples taken during the test are presented in Section IV.

The balance of the fires were conducted at the Civil Engineering Research Facility (CERF) located on Kirtland AFB in Albuquerque, New Mexico. A continuous pool of 2200 ft^2 in area with no internal obstructions was constructed on a concrete pad (Figure 22). The outer dimensions of the pool were approximately 50 by 50 feet with rounded edges. Around the edge, there was an 8-inch high berm to contain the fuel and water. The halon tank on a P-13 firetruck was charged with 440 pounds of Halon 2402. Two different nozzles were tested against this fire--a standard Air Force halon nozzle and a modified Air Force halon nozzle which had been drilled out to 0.5 inches.

Two tests were run at this location. During the tests, the fire-fighter approached the fire with the wind (2 to 3 mph) at his back. An average water depth of 3 inches was obtained before the fuel were added. For both tests, 300 gallons of JP-4 fuel were floated on the water surface. After the whole area was burning, a 10-second preburn was allowed before the fire was attacked.

For the first test, the standard Air Force P-13 nozzle was used. With this nozzle, only 60 percent of the pool could be controlled. This was mostly due to the throw range of the nozzle. As the firefighter moved around the pool to suppress the back portion of the pool fire, the far side slowly started burn-ing back. It was apparent that there was some inertion of the extinguished fuel. Agent was supplied to the fire for 84 seconds. This resulted in an application rate of 5.2 lb/s.

In the second test, a modified Air Force P-13 nozzle with a 0.5-inch orifice was used. With this nozzle, 99 percent of the fire was suppressed and controlled. The nozzle had insufficient range to completely extinguish the fire because of the lip effects the berm had on the far side of the pool. Halfway through the extinguishing run (Figure 23), the fire had been pushed to the back berm which then acted as a flame holder (Figure 24). At one point before the agent was expended, the fire was only burning on the back side of the berm in
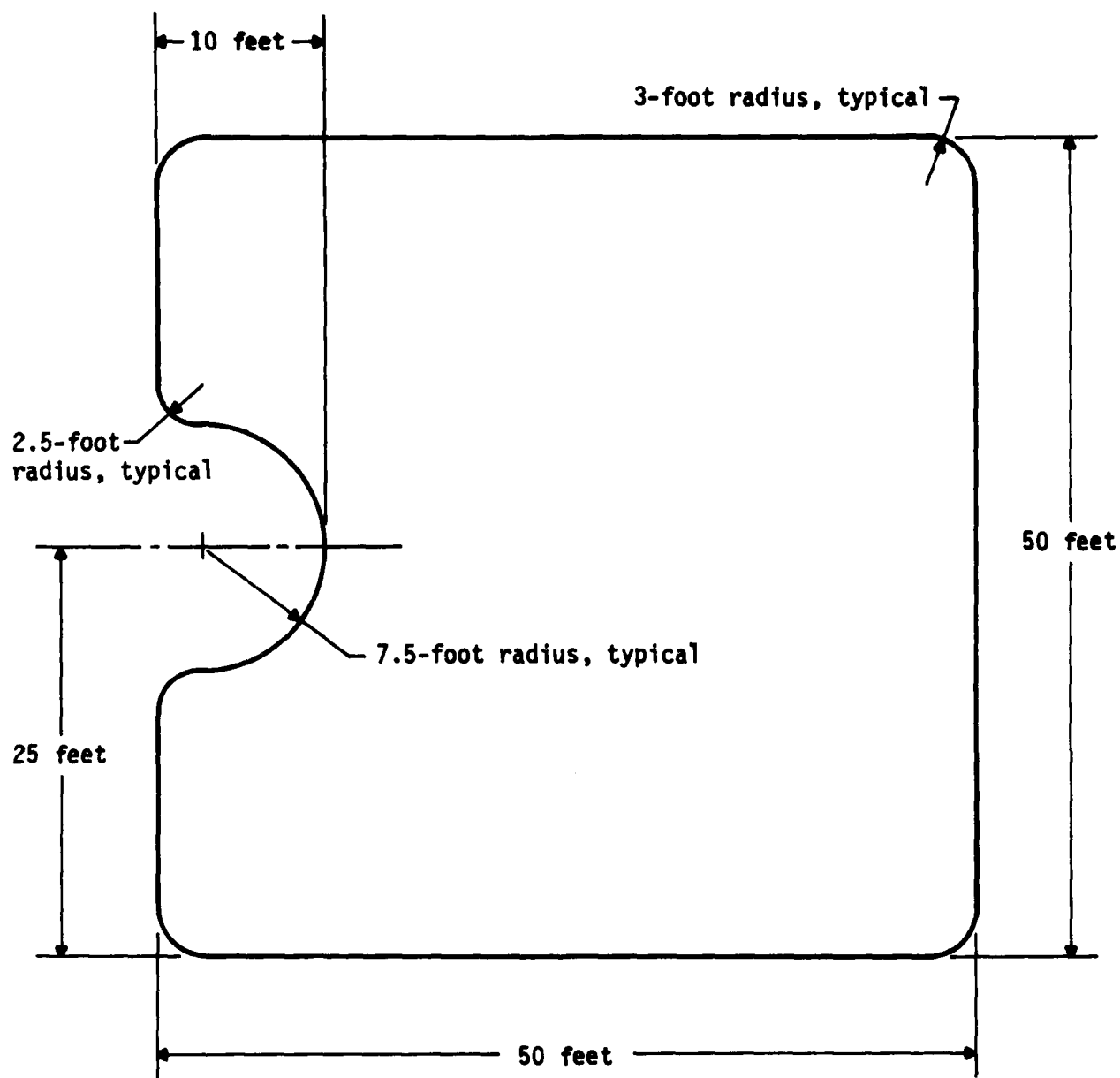
Figure 22. Shape of 2200 ft^2 Pool.
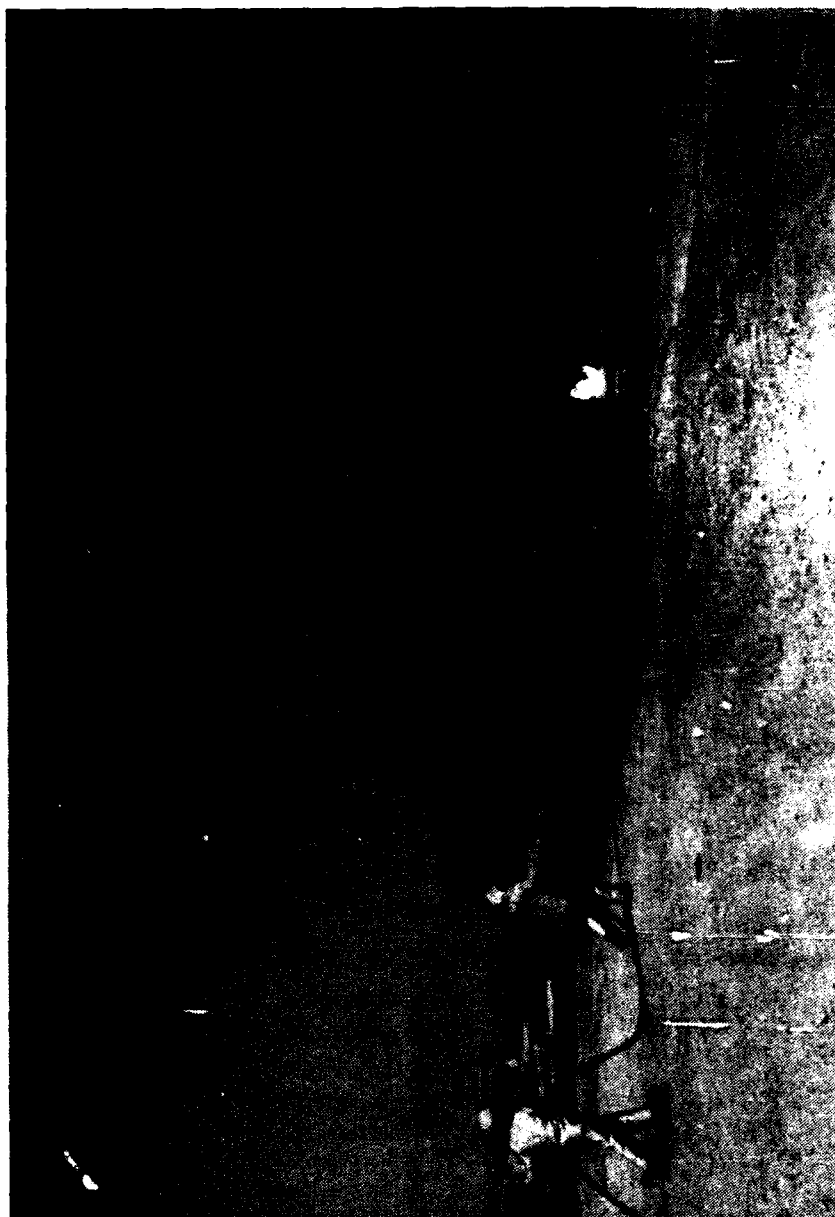
Figure 23. Extinguishment of 2200 ft^2 Pool Fire With Modified Air Force Halon Nozzle.

Figure 24. Flame Holding of Back Berm on 2200 ft^2 Pool Fire.

places. Burnback was very slow. After the fire had started burning in the pool, the flame front moved approximately 1 ft/s. While igniting the fire, the flame front traveled at approximately 5 to 7 ft/s. Although the fire had been suppressed and no surface inertion existed, the fire could flash back over the hot fuel. If this were to happen, the flame front could travel much faster then when the fuel was first ignited.

Agent application lasted 42 seconds resulting in an application rate of 10.4 lb/s. An approximate burn rate of JP-4 was calculated from data provided by the videos. The approximate specific burn rate was 0.011 $lb/ft^2/s$, which is close to the specific burn rate found for 150 ft^2 fires (0.014 $lb/ft^2/s$). The difference is probably due to the interference of Halon 2402 vapor during the burn back and postburn.

With the higher application rate obtained in the second test, both the throw range and the droplet size increased. The line losses also increased with the increase in application rate and resulted in a lower exit pressure and a larger droplet size.

4.   Test Results for C-131 Fire Suppression

Fuel pans, Class A and B combustibles, thermocouples, oxygen injectors, agent applicators, and video camera were arranged inside a C-131 aircraft as shown in Figures 25 and 26. The two 0.4 m^2 (4 ft^2) fuel pans contained approximately 9.5 liters (2.5 gallons) of JP-4 each. The 0.7 m^2 (8 ft^2) pan contained 19 liters (5 gallons) of JP-4. The chair consisted of typical aircraft Class A combustibles, such as foam and synthetic fabrics, bound to a metal frame. Two simulated penetrator nozzles (Reference 13) were used inside the aircraft to apply halons. The test nozzle was connected to a 227-kilogram (500-pound) Halon 1211 tank on an XP-13 firetruck. The second was a backup nozzle connected to a 73-kilogram (160-pound) portable Halon 1211 tank. This nozzle was pointed directly at the fuel pans from above. An AFFF line from the XP-13 firetruck was positioned near the camera box located in the tail section of the aircraft. This line was to be used for cooling the inside of the aircraft, if necessary. During most tests (Table 14), halon was injected through the simulated penetrator nozzle, either in front or behind the fuel pan. Tests were performed with both the cargo and passenger doors closed and open.
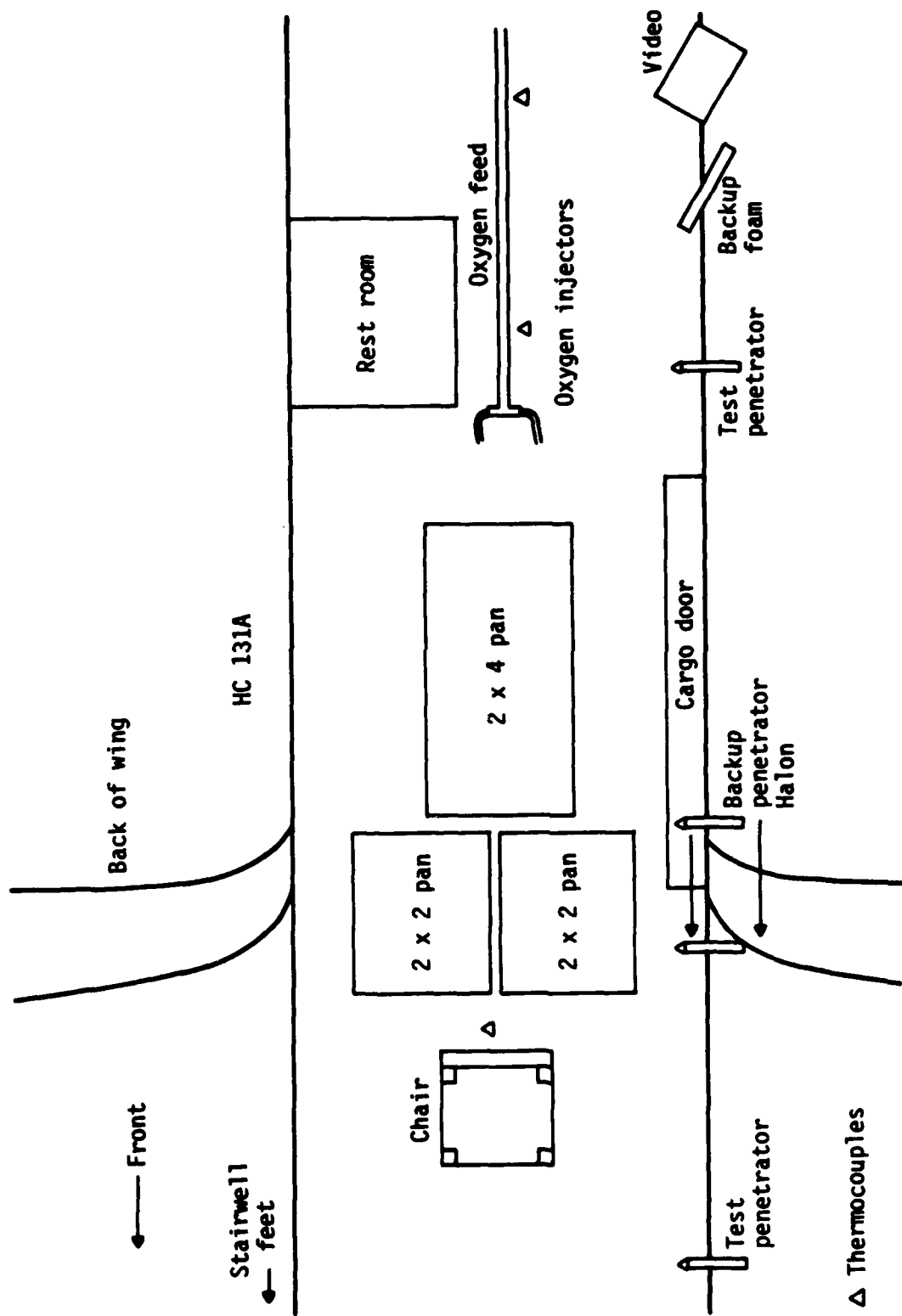
Figure 25. Large-Scale Layout in C-131 Aircraft.

Figure 26. Thermocouple Arrangement for C-131 Large-Scale Tests.
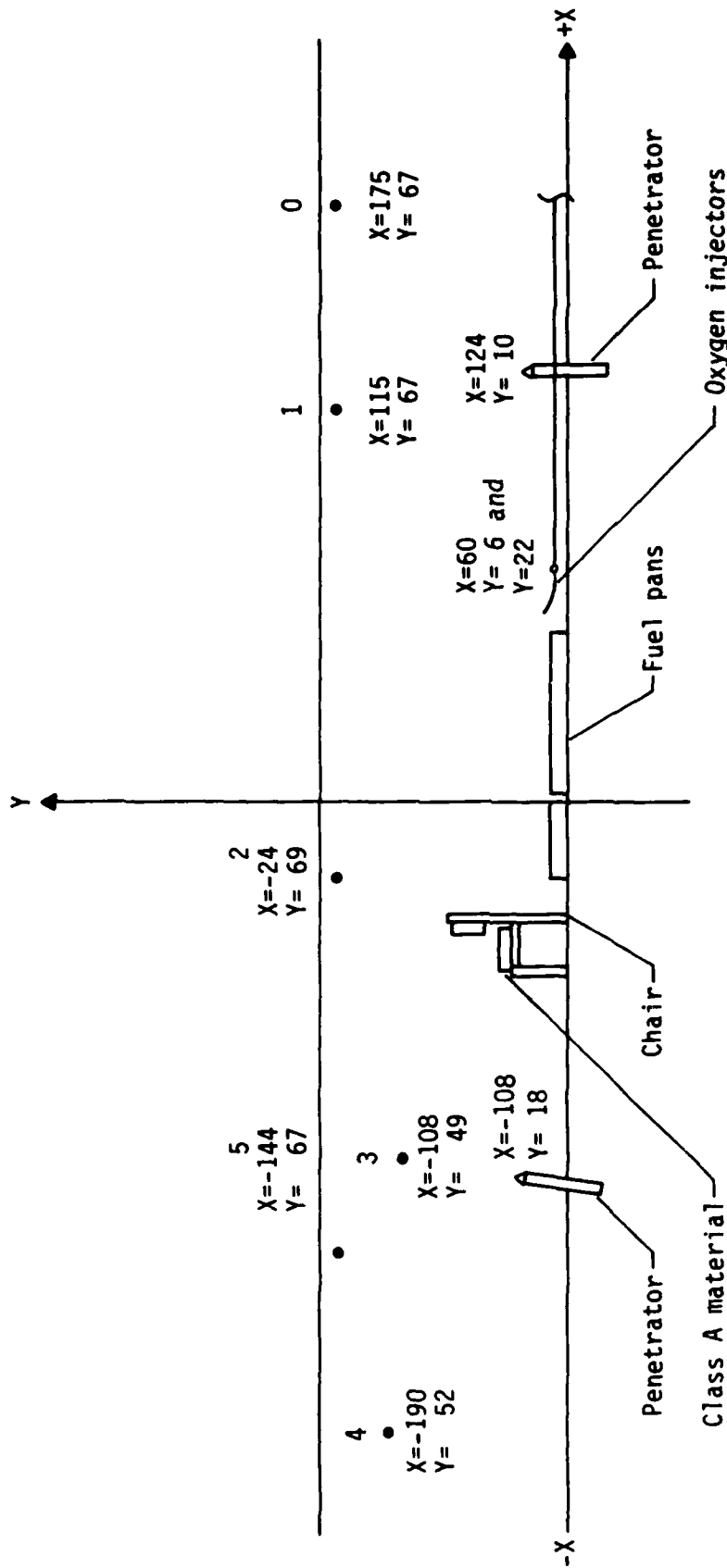
Note: All dimensions in inches unless otherwise specified.

61

TABLE 14. FULL SCALE C-131 TEST RESULTS.

Test no.	Flow type	Halon type	Halon discharge time, s	Test results	Fuel loss, kg (lb)	Oxygen loss, lb	Chair damage	Comments
1	With flow	1211	10	Suppression	N/A	N/A	Heavy	
2	With flow	1211	30	No suppression	10.5 (23.1)	5.0	Complete	Both doors open
3	With flow	2402	33	Suppression	10.0 (22.0)	6.0	Complete	Both doors open

[a]N/A = Not available

62

The penetrator nozzle (Reference 13) or skin penetrator agent-application tool (SPAAT) was chosen for this test because of its ability to drill through the skin of an aircraft and disperse halon quickly through the interior of the aircraft. Thermocouples were used because smoke obscured the view of the video camera during tests, and the only way to tell if the fire had been suppressed was by watching the thermocouple readings. The thermocouple also gave a time-temperature history inside of the aircraft. These data may be useful in other research areas. The timing of the agent application was determined by thermocouple readings and a fixed-time interval. Only Halon 2402 was able to suppress the C-131 fires without reignition in the following tests.

    a. Test 1

        In Test 1, the penetrator was located 3 meters, 102 millimeters (10 feet, 4 inches) behind the fuel pans. The aircraft was sealed during the test. The fire was ignited and preburned until thermocouple 2 reached 538 °C (1000 °F). After that point, an additional 15 seconds of preburn was allowed before suppression started. During the test, Halon 1211 was injected into the fuselage for 10 seconds. The halon was shut off when suppression was obtained. Damage to the chair was low with holes burned through the cloth on the chair, charring the foam in places. Thermocouple temperature readings from the test are shown in Figure 27. The following events occurred as shown in Figure 27.

            (1) Start of oxygen flow.
            (2) Start of Halon 1211 application.
            (3) Suppression of fire.
            (4) Reignition of fire.
            (5) Suppression of fire.
            (6) Atmosphere well mixed, conductive cooling through skin of
aircraft.

    b. Test 2

        In Test 2, the penetrator was located 3 meters, 102 millimeters (10 feet, 4 inches) behind the fuel pans. Both doors were open during the test. The preburn continued until thermocouple 2 reached 538 °C (1000 °F), at which point an additional 15 seconds of preburn continued before the fire was
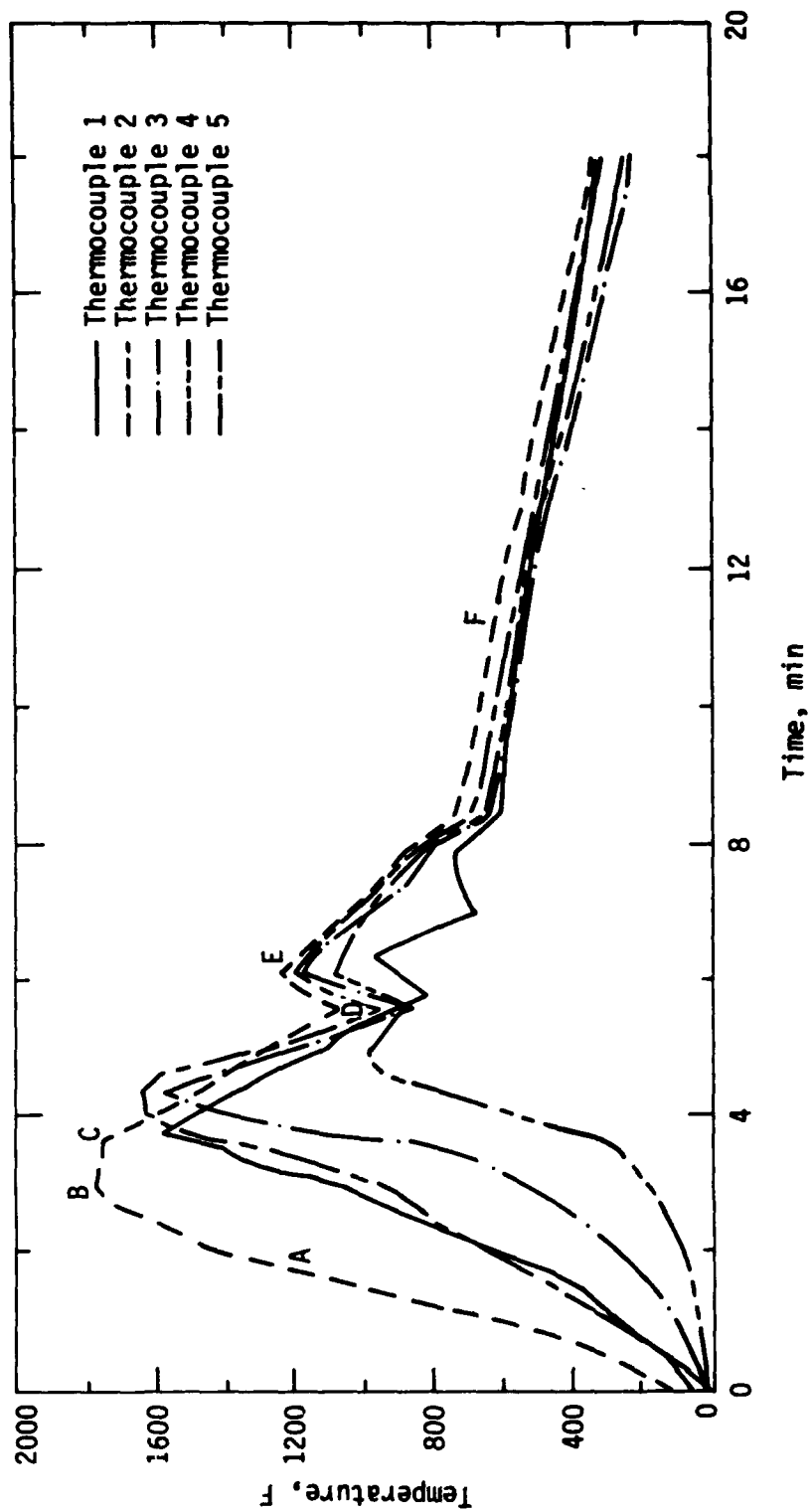
Figure 27. Time and Temperature History, Large-Scale Test 1.

suppressed. During the test, Halon 1211 was injected at the rate of 2.4 kg/s (5.4 lb/s) into the fuselage for 15 seconds. At this point, the Halon had no effect on the fire. The fire was hot and intense. Following suppression, reignition occurred and more halon was required. The chair was completely burned.

Fuel loss	Preweight, kg	(lb)	Postweight, kg	(lb)	Weight loss, kg	(lb)
Left 0.4 m² (4 ft²) pan	35	(76.1)	31	(68.5)	3.4	(7.6)
Right 0.4 m³ (4 ft²) pan	37	(81.0)	33	(72.5)	3.9	(8.5)
Center 0.7 m² (8 ft²) pan	67	(147.5)	59	(130.5)	8.0	(7.0)

c. Test 3

In Test 3, the penetrator was located 3 meters, 102 millimeters (10 feet, 4 inches) behind the fuel pans. The preburn continued until thermocouple 2 reached 538 °C (1000 °F), at which point an additional 15 seconds of preburn was allowed before suppression started. During the test, Halon 2402 was injected into the fuselage. The Halon 2402 was sorted in a wheeled unit pressurized to 1 MPa (150 lb/in.²). The initial weight of the halon was 82 kilograms (180 pounds). There was no reignition of the fire. The chair was completely burned. Thermocouple temperature readings from the test are shown in Figure 28. From Figure 28 the following events occurred:

    (1) Start of oxygen flow.

    (2) Start of Halon 2402 application.

    (3) Suppression of fire.

    (4) Atmosphere well mixed, conductive cooling through skin of aircraft.

5. Summary of Large-Scale Fire Suppression

As the outdoor fires become larger, the effectiveness of Halon 1211 is decreased. On complex fires such as those encountered with the 3-D apparatus, Halon 1211 was not able to penetrate the fire to its base. Also Halon 1211 is not able to inert the fuel surface during a fire. Only Halon 2402, with its heavier molecular weight and high boiling point, can afford a temporary inertion period.
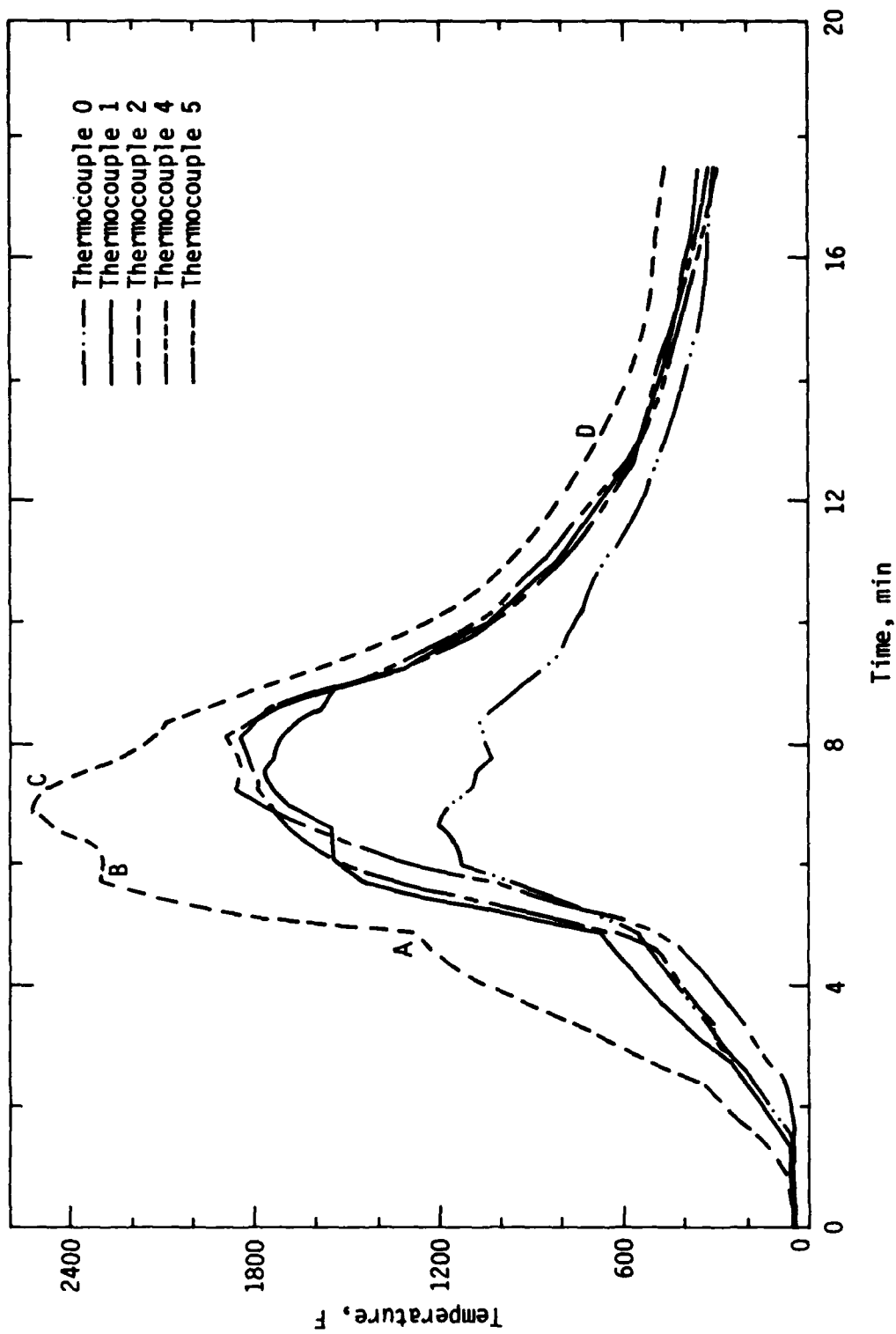
Figure 28. Time and Temperature History, Large-Scale Test 3.

Halon 1211 becomes a gas after it exits the nozzle. As a droplet leaves the nozzle, therefore, the energy in the droplet quickly dissipates as the droplet evaporates. As the momentum in the droplet becomes random, the distance it will travel is greatly reduced. With a smaller throw range, the size of fire that Halon 1211 can extinguish is greatly reduced. With a higher boiling point, a droplet of Halon 2402 takes longer to evaporate. This slower evaporation allows the droplet to travel further. The distance a droplet of Halon 2402 will travel depends on its size and its initial energy as it leaves the nozzle. By increasing either of these factors, the throw range might be expected to increase. This is not the case, however, because the initial energy at the nozzle and the droplet size are related to each other. As the energy at the nozzle increases, the size of the droplet decreases. Above a pressure of 200 lb/in.^{2}, the size of the droplet becomes so small that there is a reduction in throw range. What seems to happen is that small droplets leave the nozzle with a large amount of random kinetic energy instead of directed energy. This randomization causes formation of a cloud instead of a directed stream. Below 100 lb/in.^{2} the droplets become very large (on the order of 0.375 inch) but have insufficient energy to travel very far. The large droplets then require a large amount of heat energy to totally evaporate and interact with the fire.

For large-scale fires, a storage tank pressure of 150 to 180 lb/in.^{2} delivered a stream of medium-size droplets with a long throw range. The nozzle pressure depended on the hose size and the flow rate. For most of the tests, the pressure at the nozzle was approximately 130 lb/in.^{2}. The videos showed a noticeable difference in the spray characteristics when the exit pressure was above or below 130 lb/in.^{2}. By reducing the exit pressure some (10 to 20 lb/in.^{2}), the agent nozzle could be made more effective for very large fires. The large amount of thermal energy available in large fires could evaporate the larger droplets. This nozzle would then have a reduced ability to fight smaller (150 ft^2) fires. With the relatively small amount of energy available, the large droplets would pass through the flame front without completely evaporating.

From medium- and large-scale testing, pressure of 130 to 140 lb/in.^{2} at the nozzle was optimum. The spray characteristics at this pressure are such that a small or large fire can be effectively suppressed.

Applying Halon 2402 is different than applying Halon 1211. With Halon 1211, a vapor cloud quickly forms showing the firefighter where the fire is being suppressed. By moving the cloud around, the fire can be totally suppressed. With Halon 2402, a vapor cloud does not form quickly. A time lag is necessary to permit droplet evaporation. Even then a large cloud does not form. With the heavy density of the Halon 2402, the vapors tend to spread out over the fuel surface. A resulting small delay (up to 1 second) between application and extinguishment should be expected. This is different than the instant results obtained with the Halon 1211 cloud.

Excessive agent application was observed while the firefighters were suppressing the 2200 ft^2 fire. The firefighter would continue holding the agent stream in an area until the fire was suppressed. Testing indicated that a sweeping action is the most efficient. This spreads the agent out, allowing the vapors to work effectively against the fire. The sweeping action builds the largest vapor cloud without having spots of high halon concentration.

When compared to other halons, Halon 2402 proved to be a better agent when fighting outdoor fires. This advantage was even more noticeable with larger or more complex (3-D) fires. Halon 2402 was able to penetrate the flame front on complex fires while Halon 1211 was drafted away from the fire. Retraining of firefighters when they first use Halon 2402 will be necessary.

D.   FUEL-INERTING ABILITY

The purpose of this testing was to see if Halon 2402 had an extended inerting effect. Initial studies and observations showed that Halon 2402 had an inerting effect on liquid fuels, a characteristic warranting further study. Therefore, laboratory and field studies were performed to define what concentrations of Halon 2402 were needed to inert various fuels.

1.   Applications

The ability to suppress and inert hydrocarbon fuels allows Halon 2402 to be used in many unique applications. In ruptured fuel tanks, Halon 2402 can be used to inert the fuel. By using different tank configurations, many types of fuel tanks can be protected from fires.

68

Other firefighting agents can suppress and inert liquid fuels; however, Halon 2402 has an added advantage because it is clean and will evaporate completely after discharge.

2.   Experimental Methods

Two sets of tests were run to investigate the inerting action of Halon 2402. First, a series of laboratory-scale tests were conducted to find the concentration of Halon 2402 needed to inert 10 different types of liquid fuels. After the minimum inertion concentration for each fuel had been found, the holding period at that concentration was checked. By increasing the halon concentration, the holding period can be extended. For two of the fuels medium-scale testing of the holding period was run. This testing was done to test lip effects and surface-area-to-volume ratio effects on the inertion period.

To accomplish the laboratory-scale testing, a 3.1875-inch stainless steel pan 0.375 inch deep was used. The area of this cup was 8 in.^{2}. Each test began with 8 mL of fuel measured into a 5-liter glass beaker. The beaker was placed under a 10 mL buret which contained Halon 2402. Then 2 mL of 2402 were added to the beaker. The mixture was stirred with a glass rod and poured into a metal cup. A Bunsen burner was then passed over the mixture with the flame touching the surface. If the mixture did not ignite, the flame was immediately passed over the mixture again. If the mixture ignited, the percentage of Halon 2402 was increased until it was determined that the fuel was inerted. The percentage of Halon 2402 was either increased or decreased by one-tenth of a milliliter. The flame was passed over the mixture twice for each change in halon concentration. After determining the lowest percent Halon 2402 required to inert a specific fuel, a mixture was made at that percentage and allowed to sit in an open fume hood with a small amount of air passing over it. Every 5 minutes a Bunsen burner was passed over the mixture twice. If the mixture did not ignite, after another 5 minutes the torch was passed over the mixture. When the mixture did ignite, the holding period obtained with Halon 2402 was recorded. For the medium-scale inertion holding tests, two different pans were used. The first was a stainless steel cup 3.1875 inches in diameter with 2.094-inch walls. The second was an 8- by 8-inch steel pan with a 0.375-inch lip.

During the field test, two steel pans were constructed. The first pan was 6 feet in diameter with a 4-inch lip. The second pan was 1 foot in diameter with a 2-inch lip. Test equipment and method was taken from MIL-F-24385C which is for testing Aqueous Film Forming Foam (AFFF). During testing, only 5 gallons of fuel were used. The procedure for the 28 ft^2 fire test in the AFFF military standard was followed.

The procedure for the 28 ft^2 burnback (inertion) test was:

a. Pour 5 gallons of fuel into the 28 ft^2 pan within a 30-second period.

b. Ignite the fuel within 30 seconds of completing fueling.

c. Allow fuel to burn freely for 10 seconds.

d. Extinguish as quickly as possible.

e. Continue agent application until agent is expended.

f. Within 60 seconds of completion of agent application, set the burning 1-foot diameter pan in the center of the 28 ft^2 pan.

Information recorded during each test:

a. Type and quantity of fuel used.

b. Presence or absence of a water layer.

c. Extinguishment time.

d. Elapsed time (time between extinguishment completion and placing the 1-foot diameter pan).

e. Burnback time.

Burnback time is recorded as the time between placing the 1-foot diameter pan and when 25 percent of the 28 ft^2 pan is burning.

3. Results

Ten different fuels were tested in the laboratory. In Table 15, the concentrations of Halon 2402 needed for inertion are listed. A wide range of halon concentrations are needed to inert different types of fuel with the lighter, more volatile fuels requiring higher concentrations. Table 16 represents a list of the vapor pressure of fuels tested. Gasoline, with the highest

TABLE 15. HALON 2402 FUEL INERTION TESTS.

Test no.	Fuel	Mixture	Halon 2402, % V/V
1	Hexane	7 mL Hexane 3 mL 2402	30
2	Acetone	7 mL Acetone 3 mL 2402	30
3	Methanol	8 mL Methanol 2 mL 2402	20
4	Ethanol	9.5 mL Ethanol 0.5 mL 2402	5
5	Heptane	8.8 mL Heptane 1.2 mL 2402	12
6	JP-4	9 mL JP-4 1 mL 2402	10
7	JP-5	9.75 mL JP-5 0.25 mL 2402	2.5
8	Reg. gasoline octane--88	6.8 mL reg. gas. 3.2 mL 2402	32
9	Unleaded gas. octane--87	6.8 mL unleaded gas 3.2 mL 2402	32
10	Super unleaded gasoline octane--90	6.8 mL 3.2 mL 2402	32

TABLE 16. VAPOR PRESSURE AT 25 °C.

Fuel	Vapor pressure, torr
Methanol CH_4O	113.86
Ethanol C_2H_6O	54.235
Acetone $CH_3CO\ CH_3$	200.038
Hexane C_6H_{14}	133.258
n-Heptane C_7H_{16}	41.734
Gasoline	325.804
JP-4	129.287
JP-5	Negligible

vapor pressure, requires the highest halon concentration to obtain inertion; JP-5, with the lowest vapor pressure, requires the lowest halon concentration.

After the minimum percentage of Halon 2402 needed for inertion was found, the mixture was tested to find out how long the period of inertion lasted. The results of that testing are listed in Table 17. These times are for minimum halon concentration. By increasing the halon concentration, the time period for inertion can be increased. The results obtained for Tables 15 and 17 were gathered from laboratory Tests 1 through 10, which are presented in Appendix A.

To further test the results and to see if there were any other effects, medium-scale tests were conducted.

During Tests 11 and 12 (Appendix A), the volume of the mixture was increased by 1000 percent and the surface area was left unchanged. In addition, the wall height was increased from 0.375 inch to 2.094 inches. These changes resulted in extended inertion periods with a greatly extended period using unleaded gasoline, whose inertion period was increased from 15 minutes to 6 hours.

Due to the large inerting time found in Test 12 (Appendix A), interest was generated in determining whether the concentration of Halon 2402 needed to inert a fuel was dependent on the surface-area-to-volume ratio. In Test 13 (Appendix A), the surface-area-to-volume ratio was changed to that used in Tests 1-10. This was done with the 64-in.^{2} pan having an area 800 percent larger than Tests 1-10. When using 800 percent more fuel/halon mixture, the results obtained were similar to the earlier results. These results show that the inertion period increases as the surface-area-to-volume ratio decreases.

During Test 14 (Appendix A), a 3.1875-inch pan was used. Unleaded gasoline (80 mL) was added and during the course of the test the halon concentration was increased. The pan in which the testing was done had 2.094-inch side walls and an area of 8 in.^{2}. When the inertion period started, the mixture depth was 0.62 inch. This left a free board of 1.5 inches. With concentrations as low as 16.7 percent, Halon 2402 was able to extinguish the fire.

TABLE 17. FUEL INERTION HOLDING RESULTS,
8 in.^{2} SURFACE AREA.

Test no.	Fuel	Mixture	Halon 2402, %	Inerting time of Halon 2404, min
1	Hexane	7 mL Hexane 3 mL 2402	30	5
2	Acetone	7 mL Acetone 3 mL 2402	30	5
3	Methanol	8 mL Methanol 2 mL 2402	20	5
4	Ethanol	9.5 mL Ethanol 0.5 mL 2402	5	5
5	Heptane	8.5 mL Heptane 1.5 mL 2402	15	10
6	JP-4	9.0 mL JP-4 1.0 mL 2402	10	10
7	JP-5	9.75 mL JP-5 0.25 mL 2402	2.5	20
8	Regular	6.8 mL Regular 3.2 mL 2402	32	20
9	Unleaded	6.8 mL Unleaded 3.2 mL 2402	32	15
10	Super unleaded	6.8 mL Super-unleaded 3.2 mL 2402	32	15

After a burn of 12 seconds, sufficient agent was generated to extinguish the fire. As the concentration increased, the burn time was decreased until the mixture was inerted. On the first three concentrations, the fire was smothered as soon as it had ignited. Upon reaching 26 percent, the mixture was taken through an inertion holding test and the results showed a very long holding time. At 24 hours, the mixture was still inert and the depth had reduced to 0.31 inch corresponding to a 50 percent reduction in volume.

One of the reasons why the mixture stayed inerted so long may be that the lighter, more volatile distillate was burned off during the first part of the test. As seen from the evaporation results at 45 minutes, there was a temporary flash on the fuel surface. Then at 60 minutes, there was a 3-second burn; later at 2 hours, there was a temporary flash; after that, total inertion. If there had been more volatiles, the fire may have continued burning.

4. Inertion Tests, 28 ft² Area

To further study the inerting ability of Halon 2402, large-scale tests were conducted. The results are shown in Table 18. Since there were no inerting tests for halons, Military Test F-24385C for AFFF was used as a basis and a point of reference. The part of the military test used was that for testing the inerting capability of AFFF. The nozzle specified has a flow rate of 2 gpm applied over 90 seconds, a total of 3 gallons of agent. For halons an application period of 90 seconds is much too long. Another problem is the density difference between the two agents. Halon 2402 has a density of 2.24 g/mL at 0 °C, and AFFF has a density of less than 1.00 g/mL. For this testing, a weight/weight relationship was held. The Halon 2402 nozzle designed was a straight pipe with an orifice of 0.157 inches and flow rate of 0.57 lb/s. This resulted in a discharge time of 48 seconds.

For the test, 5 gallons of fuel were poured into a 28 ft² pan (Figure 29) and then ignited within 30 seconds. After a preburn of 5 seconds, the fire was extinguished as fast as possible and application continued until all of the agent was expended. By using a higher flow rate nozzle, the extinguishing times could have been reduced. A 1-foot diameter pan with burning fuel was then set in the middle of the 28 ft² pan (Figure 30). Burnback resistance was measured as the time required for the fire to spread over 25 percent of the

TABLE 18. INERTION RESULTS, 28 ft² AREA.

Test no.	Fuel type, 5 gallons	Amount of Halon 2402, lb	Extinguishing period, s	Agent application, s	Test pan in fuel area, s	Burn-back, s	Water layer	Wind, mph	Notes
1	Gasoline	27	29.4	46.5	13.9	0.2	Yes	75	No inertion
2	JP-4	27	7.5	49.5	25.1	0.2	Yes	75	No inertion
3	Gasoline	27	10.8	50.2	20.3	0.2	No	75	No inertion
4	JP-4	27	27.0	41.4	18.6	1.6	No	75	Burn rate
5	JP-4	0	240.0	0			Yes	75	Burn rate
6	JP-4	0	250.0	0			No	75	Reduction in burn rate
7	JP-5	1+18	2.0	10.4	19.3	76.7	Yes	75	Self-extinguished after 148 seconds; inert for 8 minutes.
8	Gasoline	23+18	39.0	48.4	30.7	34.0	No	75	
9	JP-4	19+18	31.4	55.4	54.0	2.5	No	75	Reduced burn rate

Figure 29. Burnback Test, 28 ft^2.

Figure 30.   Burnback Test Pans, 28 and 1 ft^2.

pan. For Tests 1 through 4, Halon 2402 did not show any burnback resistance.
The videos showed that the agent vaporized as fast as it was added to the fuel.
Without mixing of the liquid phase, the fuel would not be inerted.

To test this theory, 18 pounds of Halon 2402 were poured into JP-5
after the fire was extinguished. After adding the agent, the burnback resis-
tance was tested. This gave rise to another difference not usually encountered
in this test. While the 1-foot diameter pan was being lowered into the 28 ft^2
fire pan, the 1-foot diameter pan was almost extinguished. After the 77-second
burnback, sufficient halon was still present to keep the fire from quickly
spreading over the balance of the 28 ft^2 pan.

A similar test was run (Test 8), but without wind. During this test
everything behaved as in the first test until after the burnback period had
been found. The standard procedure was to burn off the excess fuel after each
test; however, during Test 8, while the fuel was burning off, the flame front
lifted off of the fuel surface and continued to rise until the fire was extin-
guished again. After another 8 minutes, the fuel reignited and completely
burned off.

Fuel inertion using Halon 2402 seems to depend on several factors:

a. Droplet size.
b. Wind conditions.
c. Fuel temperature.
d. Fuel type.

With a very small droplet, the heat of the fire completely evaporated
the droplet before it reached the fuel. With a very large droplet, insuf-
ficient halon was evaporated from the droplet to extinguish the fire
efficiently.

Because of the density of Halon 2402 vapors, a blanket of halon will
form immediately above the surface. This temporary inerting is very dependent
on the wind conditions and the size of the lip surrounding the fuel. On a calm

day, the vapors will move very little, resulting in an extended inertion period. As the wind speed increases, the inertion period decreases.

A large lip around the pool holds the vapor in, even on a windy day. In this case, a surface inertion of the air above the fuel occurs instead of actual inertion of the fuel. As soon as the vapors are blown away, the fire can reignite. On very windy days, this surface inertion is very difficult to obtain.

A water layer interfered with the fuel inertion. Water and Halon 2402 do not mix when poured together. Since Halon 2402 has twice the density, the water will float on top of it. During extinguishment, any agent which splashes through the fuel surface into the water layer will sink and be lost. During most of the testing, no water was present in the 28 ft^2 pan. In Tests 6 and 7, fires were burned to find out if a water layer would change the burn rate. In both tests, the specific burn rate was 0.005 lb/ft/s.

While using the modified nozzle designed to approximate the 2 gpm AFFF nozzle specified in the military standards, inertion was not obtained in any test. Immediately following agent application, there was some vapor present on the fuel surface. By the time the 1-foot diameter pan was placed in position, the vapors had blown away.

While surface inertion is only temporary, it is much easier to obtain. To inert JP-4, the laboratory-scale tests showed that 10 percent concentration volume/volume of Halon 2402 was needed. To inert a 1000-gallon spill, 100 gallons of Halon 2402 will be required. This volume of Halon 2402 will weigh 1800 pounds. This amount of agent will not always be present, even on a large base, to be applied all at one time. With surface inertion, on the other hand, a vapor concentration as low as 2 percent will inert the fuel. So the amount of agent needed for surface inertion is only dependent on the surface area and not the volume.

E. COMPATIBILITY OF AGENTS

Testing was done to evaluate the constructive and destructive inference of Halon 2402 and other firefighting agents.

In current and past research (References 7 and 9), a trend has become noticeable when suppressing a fire with two different agents. The military system uses two types of agents: (1) agents which suppress a fire by cooling and separating the fuel from the oxidizer (AFFF and water) and (2) agents which work chemically by breaking the radical chain (halon and dry powders). What has become noticeable when using two different agents to suppress a fire is a positive reinforcement if one of the agents is used from each group. A destructive interference has been observed if both agents are out of the same group.

Agents out of the same group suppress the fire the same way. Using both AFFF and water at the same time will result in a decrease in efficiency of AFFF. AFFF has sufficient cooling capability; water only damages the integrity of the AFFF surface.

Both dry chemicals and halon work by chemical reaction. This reaction occurs on the molecular level in the combustion zone. Since halons and dry powders react chemically through different chains, the reactions could counter-act one another. This was found to be true during a study by Geyer (Reference 10) using Halon 1211 and different types of dry powders.

Geyer (Reference 10) found a constructive interference when applying Halon 1211 and AFFF; the AFFF stream "carried" the halon, thereby, increasing the range of the Halon 1211. With the low flashback resistance of 1211, AFFF was able to secure the fuel allowing the 1211 to continue to extinguish the fire. When using one agent from each group, there is no interference during extinguishment because they extinguish a fire by following different paths. By improving the flashback resistance and throw range of Halon 1211, AFFF may work together with Halon 1211 to extinguish fires more effectively.

During medium-scale testing with Halon 2402 and AFFF, dual application of Halon 2402 and AFFF was less effective than Halon 2402 alone in extinguishing a cascading fuel fire (Reference 9). The decrease in efficiency is related to the part that the liquid Halon 2402 is to some extent carried by the AFFF stream. The halon is cooled by the AFFF as it approaches the flame front which decreases the amount of Halon 2402 that vaporizes in the flame zone. (The ability of halons to extinguish flames is related to their ability to vaporize in the flame zone.) This reduces the three-dimensional capabilities of the Halon 2402. The Halon 2402 that is carried to the fuel surface by the AFFF would sink into the fuel layer (due to the liquid density difference between AFFF and Halon 2402). This in theory could increase the burn-back resistance of the AFFF (although this was not tested) provided that the momentum of the halon droplets does not greatly disturb the integrity of the foam blanket or the presence of halon reduce the film-forming ability of the AFFF.

While Halon 2402 and water are immiscible, a small percentage of halons hydrolyzes and forms halic acids and other products. These reactive acids are corrosive and can be very destructive. With Halon 2402, the period in which halon and water are in contact can be very long. If AFFF and Halon 2402 were allowed to evaporate after being mixed, the last to evaporate would be Halon 2402. The corrosive effect will happen with all halons but will be more prevalent with Halon 2402.

81

SECTION III
DELIVERY PERFORMANCE PROPERTIES

The performance of an agent depends on physical and chemical properties affecting stability, safety, reliability, deliverability, and extinguishment capability. Knowledge of these properties permits proper design of storage, handling, and delivery systems; development of effective and safe application techniques; and avoidance of incompatible materials and situations. This section emphasizes those Halon 2402 properties which affect delivery (evaporation during delivery, trajectory performance, viscosity, density, and material compatibility). In the following section, Section IV, properties affecting safety, toxicity, environment, and human exposure are discussed. Finally, Section V presents the testing of properties and the considerations involved in the development of the proposed military specification are presented.

A. INSTRUMENTATION

Specialized instrumentation was used in the testing discussed in this and the following two sections. Repetition in the presentation of instrument features, configurations, and parameters is avoided by presenting here information common to analytical procedures in all sections.

Hewlett-Packard HP 5880A and HP 5890A gas chromatographs (GCs) were employed in several of the reported analyses. The HP 5880A GC is equipped with a flame ionization detector (FID). The HP 5890A instrument provides dual detectors--an electron capture detector (ECD) and an FID. All peak areas on the HP 5890A GC were read from the attached HP 3392A integrator. HP 5880A peak areas were taken from an HP 3350 Laboratory Automation System integrator. The peak areas have units of 1/8 microvolt-second (1/8 μV-s), which, for convenience, is designated an area unit (AU) in this report. The gas chromatograph/mass spectrometer (GC/MS) is a Finnigan Model 4600 instrument with computerized spectral matching capabilities. Helium was employed as the carrier gas for all chromatographic analyses. The characteristics of the chromatographic columns used in the analyses are described in Table 19.

TABLE 19. CHROMATOGRAPHIC COLUMN CHARACTERISTICS.

	Column 1	Column 2	Column 3
Length, m	12.5	30	25
Internal diameter, mm	0.20	0.25	0.20
Film thickness, mm	0.33	0.25	0.11
Phase	HP-1, crosslinked dimethylsilicone	SE-54, "nonpolar" 94% dimethyl, 5% diphenyl, 1% vinyl polysiloxane	Crosslinked 5% phenyl, 95% methyl, silicone
Phase ratio	150	--	--
Retention index	1437.5	--	--
Plates/meter	4600	--	--
Part/catalog number	Hewlett-Packard 19091-60312	J&W Scientific 112-5432	Hewlett-Packard 19091B-002
Instrument used in	HP 5880A GC	GC/MS	HP 5890A GC

1. Detection Limits on the HP 5880A Gas Chromatograph

The detection limits and uncertainties in quantification of small quantities were determined for the HP 5880A GC, using Column 1. The chromatography was isothermal at 30 °C with a 200:1 split ratio.

Chromatographic peak intensity (integrated peak area, A) is proportional to concentration (C) and injection volume (V),

$$A = kCV \tag{1}$$

where k is a constant of proportionality. The minimum peak integration area measurable above noise on the HP 3350 Laboratory System Integrator is 0.05 AU with an estimated standard deviation of 0.02 (40 percent). With the instrument at its highest sensitivity (attenuation -4), an injection of 100

microliters (µL) of methanol vapor at 24 parts per million (ppm)* yields an area of 1.20 AU. From this, the minimum discernable peak area of 0.05 AU corresponds to a concentration of 1 ppm. The calculated uncertainties for various concentrations of gaseous methanol and for selected gaseous hydrocarbon standards are shown in Table 20.

In many cases, peaks which are too small to be detected by the integrator can still be detected visually. In this case, the peak height, H, measured from the graphical output, can be used. For small, sharp peaks,

$$H = k'CV \tag{2}$$

TABLE 20. UNCERTAINTIES IN GAS QUANTIFICATIONS.

Concentration, ppm	Uncertainty, percent			
	Methanol	Methane	Ethane	Propane/butanes
1	40.0	----	----	----
2	20.0	84.0	40.0	23.0
4	----	43.0	22.0	11.0
10	10.0	14.0	9.0	5.0
25	1.3	10.0	4.0	2.0
50	0.6	6.0	2.0	1.0
100	0.4	5.0	1.0	0.6

A 1 ppm solution of methanol in water gives peak heights of 6 and 11 mm for injection volumes of 0.2 and 0.5 uL. It is estimated that a peak height of 3 mm can be detected. This indicates that 0.5 ppm of methanol can be detected and quantified. The uncertainty in quantification, however, is large. For a peak of 3 mm, the minimum detectable peak height, the standard deviation above noise, is estimated at 1 mm (30 percent error).

---

*Unless specifically stated otherwise, all concentrations expressed in parts per million (ppm), parts per billion (ppb), or percent (%) are calculated on a volume basis.

This work shows that gaseous hydrocarbons and methanol down to 1 ppm can be detected and quantified. Similar or slightly better detection limits exist for liquid samples.

2.   Detection Limits on the HP 5890A Gas Chromatograph

A 1 µL aliquot of a solution of 0.1 µL of toluene in 50 mL n-pentane was injected into the HP 5890A GC employing a 100:1 split ratio, a 50 °C iso-thermal column (Column 3), and detector and injection temperatures of 200 °C and 250 °C, respectively. The solution had a concentration of 2 ppm toluene, and the amount of toluene in the injection was 1.7338 nanograms (ng). The FID easily detected the toluene, the integrator giving an absolute peak area of 3000 AU. Since the split ratio was 100:1, these data imply a good detectabil-ity for 1 µL of a solution containing 10 parts per billion (ppb) or 17.4 pico-grams (pg) of toluene. Additional work showed that 0.174 pg of toluene cannot be detected. An intermediate amount, 1.74 pg, can be detected but cannot be easily quantified. These data show that the detectability limit for toluene with a splitless injection is slightly more than 1 pg.

A similar study using a 1 µL aliquot of a 20 ppm solution of Halon 2402 in 50 mL toluene shows that, with a 50:1 split, 43.28 ng of Halon 2402 can be detected with the FID (peak area = 1100 AU). Taking the split ratio into account gives 865 pg as the actual amount of Halon 2402 going onto the column. These data indicate that approximately 100 pg of Halon 2402 can be detected with a splitless injection.

B.   STREAM TRAJECTORY AND EVAPORATION

1.   Objectives

Evaporative losses upon application of Halon affect both operator safety (see Section IV) and agent performance. Computer modeling of Halon 2402 evaporation and trajectory, as a function of droplet size and other flow vari-ables, are reported here. The results may be used to determine optimum nozzle configuration and application technique for delivering Halon 2402. Note that this section treats delivery without consideration of extinguishment.

2.   Overview

A computer study has been performed to determine the relative effects of temperature and droplet size on evaporation rate and stream trajectory of

85

Halon 2402 liquid. The results provide estimates of the deliverability of Halon 2402 to a fire. The simplest case--that of a single drop moving through clean air--is treated. The step-by-step procedure used in development of the algorithm for the computer program "TRAJECTORY" is contained in Appendix B. The following is a conceptual overview of the calculations.*

As a single drop passes through the air, evaporation occurs to decrease the mass. This evaporation affects not only the amount of material delivered to the fire, but also the trajectory owing to momentum and air friction changes. The evaporation rate depends on drop size and ambient and liquid temperatures. Two distinct physical regimes may apply, with a transition region in between.

In the first case, for a droplet passing through a hot gas, the thermal driving force is so large that the surface temperature of the liquid immediately rises to its boiling point and the droplet is surrounded by a film of pure vapor moving away from the liquid surface. In such cases, molecular diffusion is not relevant, and the evaporation is driven only by the thermal effects. Many such studies have been accomplished for the purpose of designing oil burners or diesel engines (Reference 14). The present study, however, has not been extended to this regime since field data may be more useful for this case.

In the second case, where a liquid has a relatively low boiling point compared to the gas temperature and the thermal driving force is very low, the surface temperature of the drop falls until the heat input makes up the heat needed for evaporation. Such regimes are diffusion controlled. Halon 2402, as a liquid in ambient air, falls into this latter category.

The lifetime, t, of a spherical droplet can be accurately determined, for certain conditions, by the expression $t = d_0^2/w$, where d_0, is the initial diameter and w is the evaporation coefficient expressed in units of area/time (Reference 15). As the relative motion between droplet and gas increases,

---

* The computer program "TRAJECTORY" manipulates, inputs, and outputs all data in English units. For that reason, only English units are used here and in Appendix B.

w also increases significantly (due to the correction factor for forced convection) and lifetimes become much shorter. The evaporation coefficient is proportional to ln $(1 + B)$. Here B is the transfer number, equal to $C_p (T_{gas} - T_{liq})/Q$, C_p is the heat capacity of the gas, and Q is the sensible plus latent heat required to evaporate the liquid. As the droplet enters the heated gas, both $\Delta T = T_{gas} - T_{liq}$ and the transfer number increase.

Though this d-squared law is widely used in the combustion industry to give estimates of droplet lifetime in hot gases, a different approach was taken in the present calculations for several reasons. First, in the present calculations, the droplets do not evaporate completely and the lifetime of a droplet is not calculated. All experimental correlations of the d-squared law are for total lifetime. Second, the d-squared law is oversimplified. During total droplet evaporation, only conditions and properties averaged over the life of the droplet are important. On the other hand, in a partial droplet evaporation, it is important to know the time dependence of properties and conditions. The d-squared law is a simplified, integrated form. Third, in conditions of high volatility and low-temperature difference, the liquid surface temperature will be at a modified or pseudo-wet-bulb value. This temperature must be calculated using correlations which estimate the ratio of instantaneous evaporation rate to heat transfer rate.

The calculations used here of liquid surface temperature and evaporation rate are based on the classic Froessling equation (Reference 16) and on laboratory data obtained over many years. The calculations consider the droplet diameter, physical properties of the liquid and gas phases, and the mutual diffusivity of the gas and liquid. The diffusivity estimated by methods given in Reference 17 is close to that given by one Halon 2402 manufacturer, Montedison (Reference 4). The given value is used in all calculations.

The wet-bulb temperature, by definition, is obtained when the liquid supplied to the evaporating surface is already at the temperature of the surface. If the liquid is warmer, the wet-bulb reading will be higher than the true wet bulb. The pseudo-wet-bulb concept assumes that some of the heat of vaporization is used to cool the surface of the droplet to a temperature close to, but slightly warmer, than that of the true wet bulb.

In the most general case, the liquid droplet surface temperature approaches the wet-bulb temperature of the liquid/gas system unless prevented from doing so by boundary conditions. The upper limit is the liquid boiling point. The lower limit is the temperature at which the vaporizing liquid forms frost (Reference 18). A second limit is posed by the vapor concentration in air. When a jet of many droplets is projected, the vapor concentration increases, particularly at the centerline, and the evaporation rate slows. There is much less cooling effect as a result.

The much more complex case, which is not considered here, is the projection of a stream of vaporizing liquid droplets through a gas. The major differences are the greatly increased momentum of the liquid and vapor relative to a single drop, and the decreased vaporization rate at the center of the jet. One program which accounts for radial and axial variations in properties of a jet, using conservation of mass, momentum, mixture fraction, and turbulent kinetic energy, is GENMIX (Reference 19).

3. Computation and Final Results

The FORTRAN computer program "TRAJECTORY" (Table 21) performs the evaporation and trajectory calculations. The computation is performed in the following order. (1) The initial diameter and velocity (including direction and height) of the drop and the temperatures of the air and liquid are inputed. (2) The program calculates a new velocity and direction.for a short time interval. (3) The evaporation rate is based on the initial velocity and diameter. (4) A new weight and diameter are calculated. (5) The new weight and diameter are used to calculate the trajectory in the next time increment. The interactive computer program input requires the initial droplet diameter D_o in inches, the initial velocity in feet/second, the nozzle height in feet, the ambient and liquid Halon 2402 temperatures in °F, and the nozzle inclination angle in degrees. The output gives the droplet diameter ratio D/D_o, mass ratio M/M_o, height y, and distance x as functions of time.

TABLE 21.   LISTING OF FORTRAN PROGRAM "TRAJECTORY."

```
1        program trajectory
2        character*64 outfile
3        real n, mass, mass0, ky, kair, k2402, krm, ksm, k, hyoky, lambda
4        real mom0, mu2402, muair, mufair, mufilm, mwfilm
5        data rho24021 / 135.47 /, grvconst / 32.174 /, pi / 3.14159265/
6        write(*,7)
7 7      format(' enter the name of the output file: '\)
8        read(*,'(a)') outfile
9        open ( 4, file = outfile )
10 1     x = 0.
11       ipar = 0.
12 5     write(*,10)
13 10    format(' enter the initial droplet diameter (inches): '\)
14       read(*,*) dia
15       if ( dia .le. 0.0 ) go to 999
16       write(*,20)
17 20    format(' enter the initial droplet speed (ft/sec): '\)
18       read(*,*) speed
19       if ( ipar .eq. 1 ) go to 59
20       write(*,30)                              ..
21 30    format(' enter the initial angle of the droplet (deg): '\)
22       read(*,*) angle
23       write(*,40)
24 40    format(' enter the height of the nozzle above the ground (ft): '
25       & \)
26       read(*,*) y
27       write(*,50)
28 50    format(' enter the ambient air temperature (F): '\)
29       read(*,*) tamb
```

TABLE 21. LISTING OF FORTRAN PROGRAM "TRAJECTORY" (CONTINUED).

```
30        write (*,52)
31 52     format(' enter the droplet temperature (F): '\)
32        read (*,*) tdrop
33        write(*,55)
34 55     format(' enter the time step to use for the calculations: '\)
35        read(*,*) dt
36 c ------------- print out initial conditions ---------------------
37        write(4,300)
38 300    format(7x,' Initial conditions'/)
39        write(4,301) dia,tamb,speed,angle,y,dt
40 301    format(7x,' Diameter (inches): ',f5.4,17x,
41        & 'Ambient Temperature (F): ',f4.0,/,7x,' Speed (fps): ',f5.1,

42        & 23x,'Angle (deg): ',f3.0,/,7x,
43        & ' Nozzle height above ground (ft): ',f4.1,4x,'Time step (sec): '
44        & ,f4.3,//))
45        write(4,302)
46 302    format(9x,'Time',12x,'D/Do',12x,'M/Mo',11x,'X',13x,'Y')
47        write(4,303)
48 303    format(9x,'(sec)',41x,'(ft)',10x,'(ft)')
49 c ------------ convert units and initialize variables --------------
50        dtime - dt / 3600.
51        angle = angle * 0.017453293
52        velx = speed * cos(angle)
53        vely = speed * sin(angle)
54        muair = 6.72e-04 * ( 0.0162 + 0.002 * ( tamb - 10. ) /90.)
55        rhoair = 0.075 * ( 530. / ( tamb + 460. ) )
56        icount = 0
57 c --------------- estimate a twb -----------------------------------
```

90

TABLE 21. LISTING OF FORTRAN PROGRAM "TRAJECTORY" (CONTINUED).

```
58        counter = 0.

59        twbg = 5.

60 105    counter = counter + 1.

61        tfilm = ( tamb + twbg ) / 2.

62 c -----------------calculate a twb based upon guess ----------------

63        vf2402 = 10. ** ( 3.752 - 2177.13 / ( 460. + twbg ) )

64        mwfilm = vf2402 / 2. * 259.8 + ( 1. - vf2402 / 2. ) * 28.95

65        cpfilm = ( 1.4712 * vf2402 + 1. ) / (15.92 * vf2402 + 4. )

66        a = 1. / ( 1. - vf2402 )

67        phi = vf2402 / log( a )

68        rhofilm = 530. / ( 460. + tfilm ) * ( 0.2985 * vf2402 + 0.075)

69        mufair = 0.0162 + 0.002 * ( tfilm - 10.) / 90.

70        mu2402 = 0.011 + 0.0023 * ( tfilm - 10 ) / 90.

71        mufilm = 2.42 * ( mufair * ( 1. - vf2402 / 2. ) * 5.38237 +

72       & mu2402 * vf2402 /2. * 16.1183 ) / ( ( 1. - vf2402 / 2. ) *

73       & 5.38237 + vf2402 / 2. * 16.1183 )

74        dm = ( 4.5869 * vf2402 + 1.1525 ) * ( tfilm + 460. ) ** 1.5 /

75       & mwfilm / 1.0e+06

76        kair = 0.014 + ( 2.44e-05 * ( tfilm - 32. ) )

77        k2402 = 0.0031 + 8.89e-06 * ( tfilm - 10. )

78        ksm = vf2402 / 2. * k2402 + ( 1. - vf2402 / 2. ) * kair

79        krm = 1./ ( vf2402 / 2. / k2402 + ( 1. - vf2402 / 2. ) / kair )

80        k = ( ksm + krm ) / 2.

81        lambda = 56.152 +0.11 * twbg - 0.166 * tdrop

82        hyoky = mwfilm * cpfilm *

83       & ( ( mufilm / dm / mwfilm ) / ( cpfilm * mufilm / k ) ) ** 0.66667

84        twb = tamb - 2. * 259.8 * lambda * vf2402

85       & /(2. * phi * hyoky - 259.8 * 0.11 * vf2402)

86 c ---------------- check for accuracy of guessed twb ----------------

87        diff = abs ( twbg - twb )

88        if ( diff .le. 1. ) go to 59
```

TABLE 21. LISTING OF FORTRAN PROGRAM "TRAJECTORY" (CONTINUED).

```
89         twbg = twbg - 0.25 * ( twbg - twb )
90         if ( counter .gt. 200. ) go to 106
91         go to 105
92 106     write (4,107) twb,twbg
93 107     format(' unable to converge on Twb after 200 iterations.',/,
94         & ' current values are:  Twb(guess) ',f5.0,/,22x,'Twb(calc)  ',
95         & f5.0,/,' Twb(guess) is used for further calculations')
96 59      dia = dia /12.
97         mass = 0.52359878 * dia**3 * rho24021
98         mass0 = mass
99         dia0 = dia
100        time = 0.
101        if ( icount .eq. 0 ) go to 110
102 c ----------- begin loop to calculate trajectories and evaporation --
103 60     time = time + dt
104 c ----------- calculate Reynolds Number for use in drag calculations -
105        reynum = dia * speed * rhoair / muair
106        if ( reynum .le. 1.9 ) go to 70
107        if ( reynum .gt. 500.) go to 80
108 c ---------- Reynolds Number between 1.9 and 500 ------------------
109        b1 = 18.5
110        n = 0.6
111        go to 100
112 c ---------- Reynolds Number less than 1.9 ----------------------
113 70     b1 = 24.
114        n = 1.
115        go to 100
```

TABLE 21. LISTING OF FORTRAN PROGRAM "TRAJECTORY" (CONTINUED).

```
116 c --------- Reynolds Number between 500 and 200000 ----------------
117 80     if ( reynum .gt. 200000.) go to 90
118        bl = 0.44
119        n = 0.
120        go to 100
121 c --------- Reynolds Number greater than 200,000 ------------------
122 90     write(*,95) reynum
123 95     format(' Reynolds Number is ',f9.0,/,' which is greater than '
124        & 'the maximum allowed value of 200,000.'/)
125        ipar = 1
126        go to 5
127 c ----------- calculate drag, velocity and position --------------
128 100    drag = muair**n * bl * pi * ( dia * speed )**(2.-n) *
129        & rhoair**(1.-n) / 8. / grvconst
130        accelx = - ( drag * cos(angle) ) / ( mass / grvconst )
131        accely = - drag * sin(angle) / ( mass / grvconst ) - grvconst
132        x = x + velx * dt + accelx * dt**2 / 2.
133        y = y + vely * dt + accely * dt**2 / 2.
134        velx = velx + accelx * dt
135        vely = vely + accely * dt
136        a = velx**2 + vely**2
137        speed = sqrt ( a )
138        a = vely/speed
139        angle = asin( a )
140 c ---------------- calculate evaporation rate coefficient ---------
141 109    a = mufilm / mwfilm / dm
142        ky = 2. * dm / dia * ( 1. + 0.276 * sqrt( reynum ) *
143        & ( a ) ** 0.3333333 )
144 c ---------------- calculate mass evaporated --------------------
145        asurf = pi * dia**2
```

TABLE 21. LISTING OF FORTRAN PROGRAM "TRAJECTORY" (CONCLUDED).

```
146        a = 1. / ( 1. - vf2402 )
147        delm = dtime * 259.8 * ky * asurf * log( a )
148        oldmass = mass
149        mass = mass - delm
150        dia = ( 6. * mass / rho24021 / pi ) ** 0.3333333333
151 c --------------- calculate dimensionless parameters and print ----
152 110    dod0 = dia / dia0
153        mom0 = mass / mass0
154        write (4,200) time,dod0,mom0,x,y
155 200    format(9x,f4.2,10x,f7.5,9x,f7.5,7x,f5.1,9x,f5.1)
156        if ( mom0 .le. 0.005 ) go to 1
157        if ( y .le. 0.0 ) go to 1
158        icount = icount + 1
159        go to 60
160 999    continue
161        stop
162        end
```

Calculations are reported for five variations--changes in the droplet diameter from 0.05 to 0.25 inch, in the initial trajectory angle from 0 to 45 degrees, in the ambient temperature from 30 °F to 110 °F, in the liquid temperature from 30 °F to 110 °F, and in the velocity from 25 to 95 ft/s. In each series of calculations, other input variables are kept constant. In all calculations, the nozzle height is set at 4 feet. The generated data are presented in Tables C-1 through C-22, Appendix C. Calculated trajectories for each run are shown in Figures C-1 through C-22, Appendix C. The calculated mass changes are shown graphically in Figures C-23 through C-44. Composites of those figures are presented in this section. Table 22 presents calculated parameters at the end of the trajectory. The runs in this table are presented in the same order as they are in the tables and figures of Appendix C.

94

TABLE 22. CALCULATED VARIABLES AT TERMINAL POINT OF DROPLET TRAJECTORY.

Initial parameters					Final parameters		
Diameter, inches	Velocity, ft/s	Temperature, °F		Angle, deg	Diameter ratio D/D	Mass ratio M/M_o	Distance, ft
		Liquid	Ambient				
0.05	45	50	70	0	0.964	0.896	16.7
0.10	45	50	70	0	0.987	0.962	19.2
0.20	45	50	70	0	0.996	0.996	20.8
0.25	45	50	70	0	0.997	0.990	21.1
0.10	45	50	70	15	0.979	0.938	29.1
0.10	45	50	70	30	0.971	0.916	34.6
0.10	45	50	70	45	0.965	0.898	34.3
0.10	45	50	30	0	0.991	0.973	18.9
0.10	45	50	50	0	0.989	0.968	19.1
0.10	45	50	90	0	0.986	0.957	19.2
0.10	45	50	110	0	0.984	0.953	19.3
0.10	45	30	70	0	0.988	0.964	19.1
0.10	45	70	70	0	0.987	0.961	19.2
0.10	45	90	70	0	0.986	0.958	19.2
0.10	45	110	70	0	0.985	0.957	19.2
0.10	25	50	70	0	0.990	0.970	11.4
0.10	35	50	70	0	0.988	0.966	15.5
0.10	55	50	70	0	0.986	0.959	22.8
0.10	65	50	70	0	0.985	0.957	26.0
0.10	75	50	70	0	0.984	0.954	29.2
0.10	85	50	70	0	0.984	0.952	32.2
0.10	95	50	70	0	0.983	0.950	35.0

4. Discussion

The effect of the initial droplet diameter on trajectory (Figure 31) is relatively small for drop diameters above 0.05 inch. The increasing range with increasing drop size tends toward a limit around 0.20 inch (Table 22). The data indicate that below 0.05 inch, the decrease in obtainable range may be unacceptable.

The effect of drop size on mass loss, as determined by the ratio of drop mass to the initial mass (Figure 32), is much larger than the effect on trajectory. The data indicate that above a drop size of 0.20 inch, the variation is negligibly small. For diameters less than 0.05 inch, the mass loss is large. One Halon manufacturer (Reference 4) recommends a drop size of 0.5 to 1 mm (approximately 0.02 to 0.04 inch). Such diameters will give very high evaporation losses.

Range, of course, increases with the initial trajectory angle (Table 22 and Figure 33). The optimum angle for range with a droplet diameter of 0.10 inch and a drop velocity of 45 ft/s is about 37 degrees. Owing to frictional losses, this angle is decreased from the optimum of 45 degrees calculated for a nonevaporating drop in the absence of friction. As seen in Figure 34, the mass loss due to evaporation for a given distance traveled increases with initial angle owing to an increased time of travel. For example, angles of 30 and 45 degrees provide nearly identical ranges; however, the latter angle gives much larger evaporative losses. For a drop size of 0.10 inch, the evaporative loss for 0.5 seconds of travel under a variety of conditions (nozzle angle, velocity, temperature) varies from 4.6 to 1.2 percent with an average loss of 3.6 percent. At very large drop sizes (2 inches), the evaporative losses decrease to 0.012 percent for a travel time of 0.5 seconds. The latter figure is a good approximation for the maximum losses in a solid stream or in one only slightly broken up.

Ambient temperature has almost no effect on drop trajectories calculated for Halon 2402. Moreover, the effect on mass loss due to evaporation is also relatively small (Figure 35). The Halon 2402 liquid temperature has an even smaller effect on trajectory and evaporative losses (Figure 36) as long as the temperature is below the boiling point. The computer program EVAP cannot handle situations where boiling occurs.

96
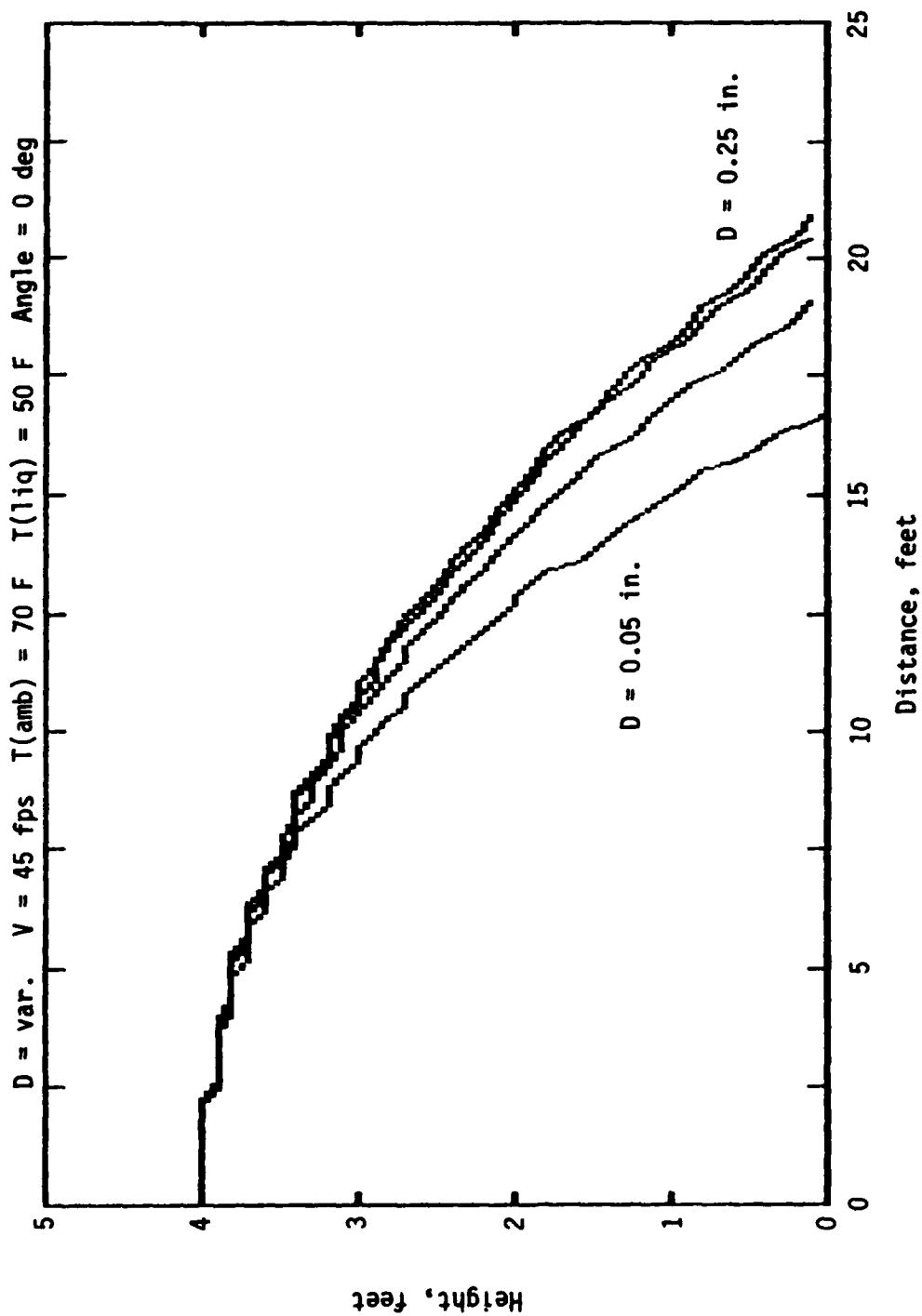
Figure 31. Effect of Drop Diameter on Calculated Trajectory for Diameters of 0.05, 0.10, 0.20, and 0.25 inch; Velocity of 45 ft/s; Ambient Temperature of 70 °F; Liquid Temperature of 50 °F; and Initial Angle of 0 degrees.
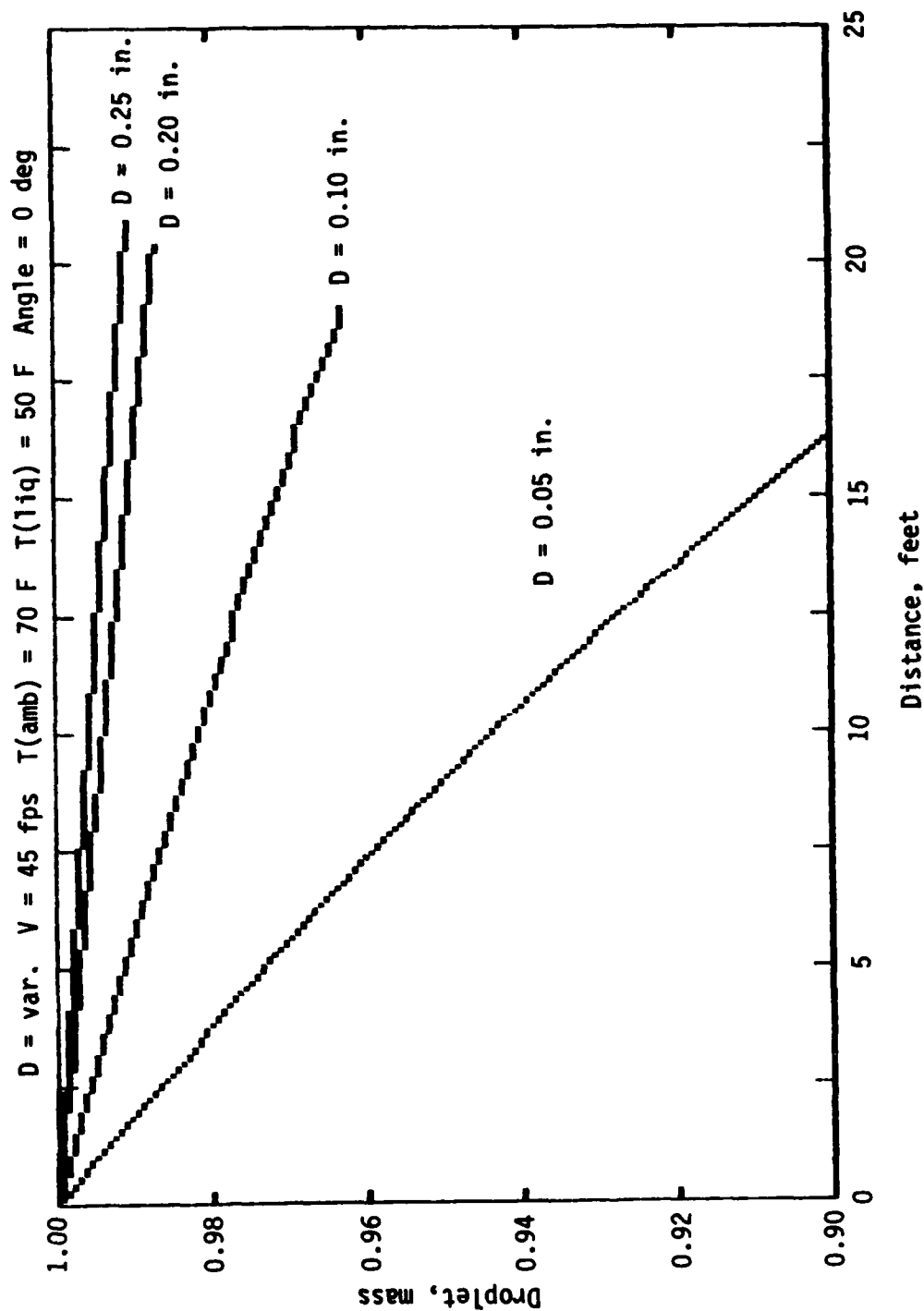
Figure 32. Effect of Drop Diameter on Calculated Mass Loss for Diameters of 0.05, 0.10, 0.20, and 0.25 inch; Velocity of 45 ft/s; Ambient Temperature of 70 °F; Liquid Temperature of 50 °F; and Initial Angle of 0 degrees.

D = 0.10 in. V = 45 fps T(amb) = 70 F T(liq) = 50 F Angle = var.
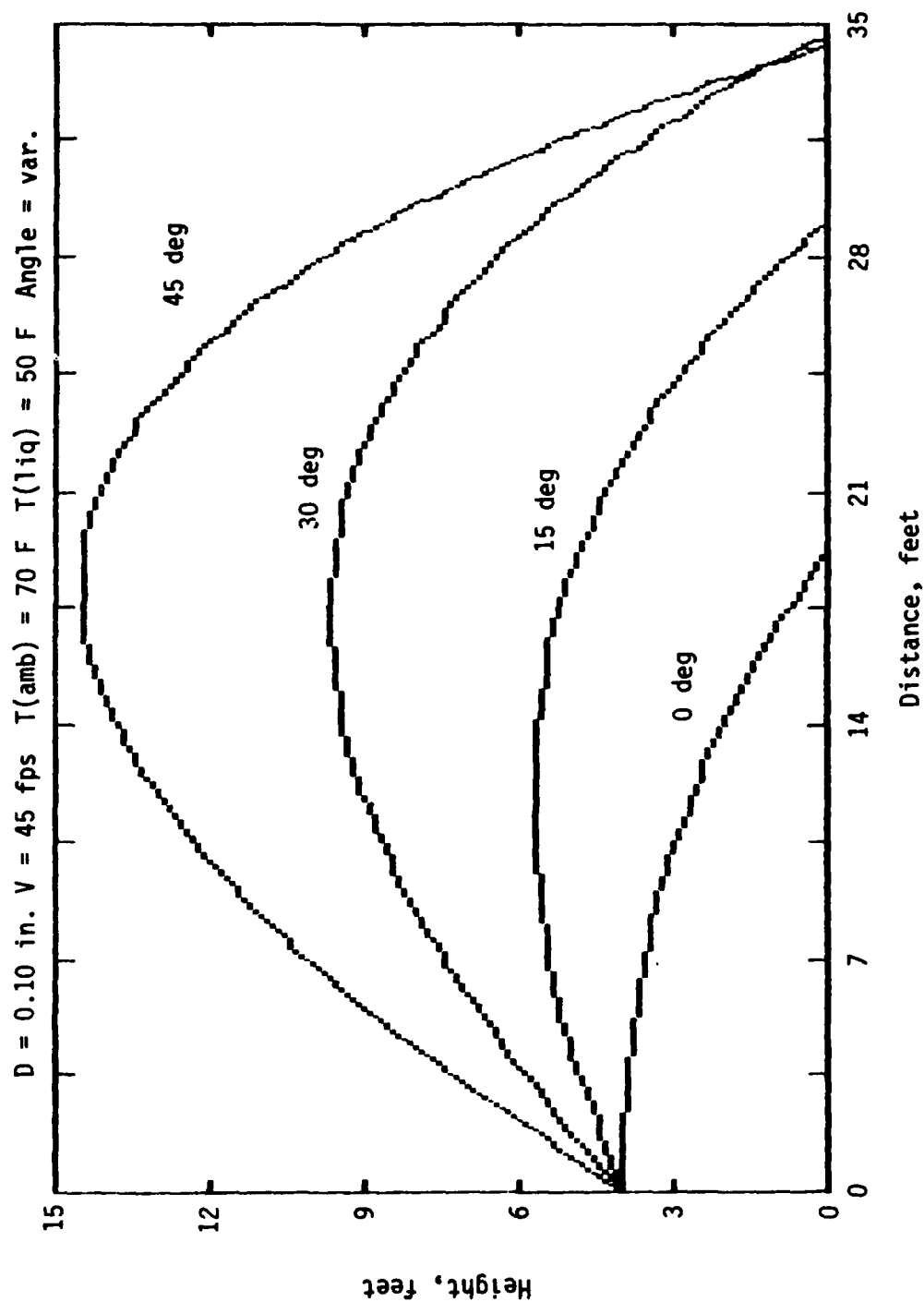
Figure 33. Effect of Initial Trajectory Angle on the Calculated Trajectory for Drop Diameter of 0.10 inch; Velocity of 45 ft/s; Ambient Temperature of 70 °F; Liquid Temperature of 50 °F; and Angles of 0, 15, 30, and 45 degrees.
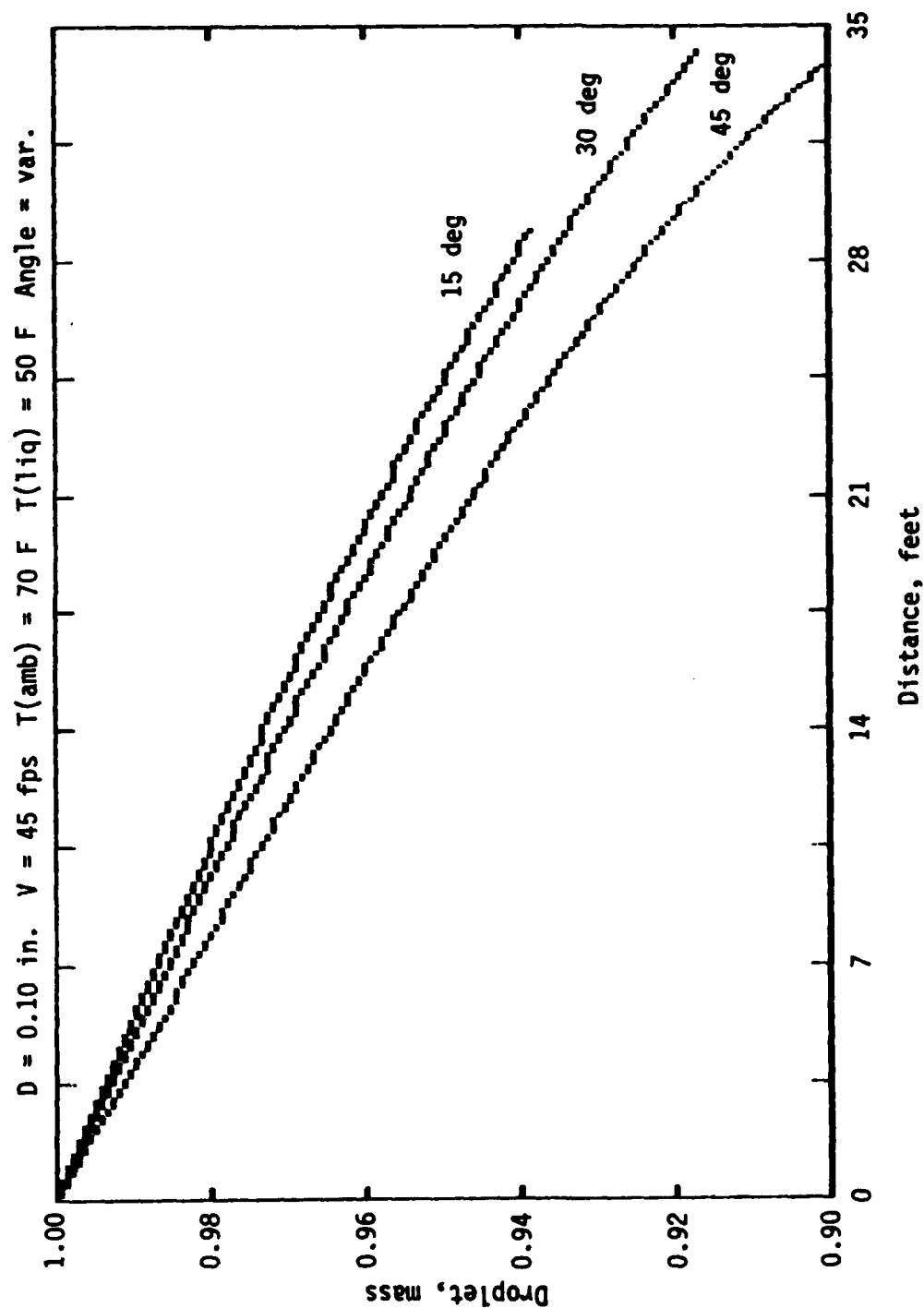
Figure 34. Effect of Initial Trajectory Angle on Evaporative Mass Loss for Drop Diameter of 0.10 inch; Velocity of 45 ft/s; Ambient Temperature of 70 °F; Liquid Temperature of 50 °F; and Angles of 0, 15, 30, and 45 degrees.
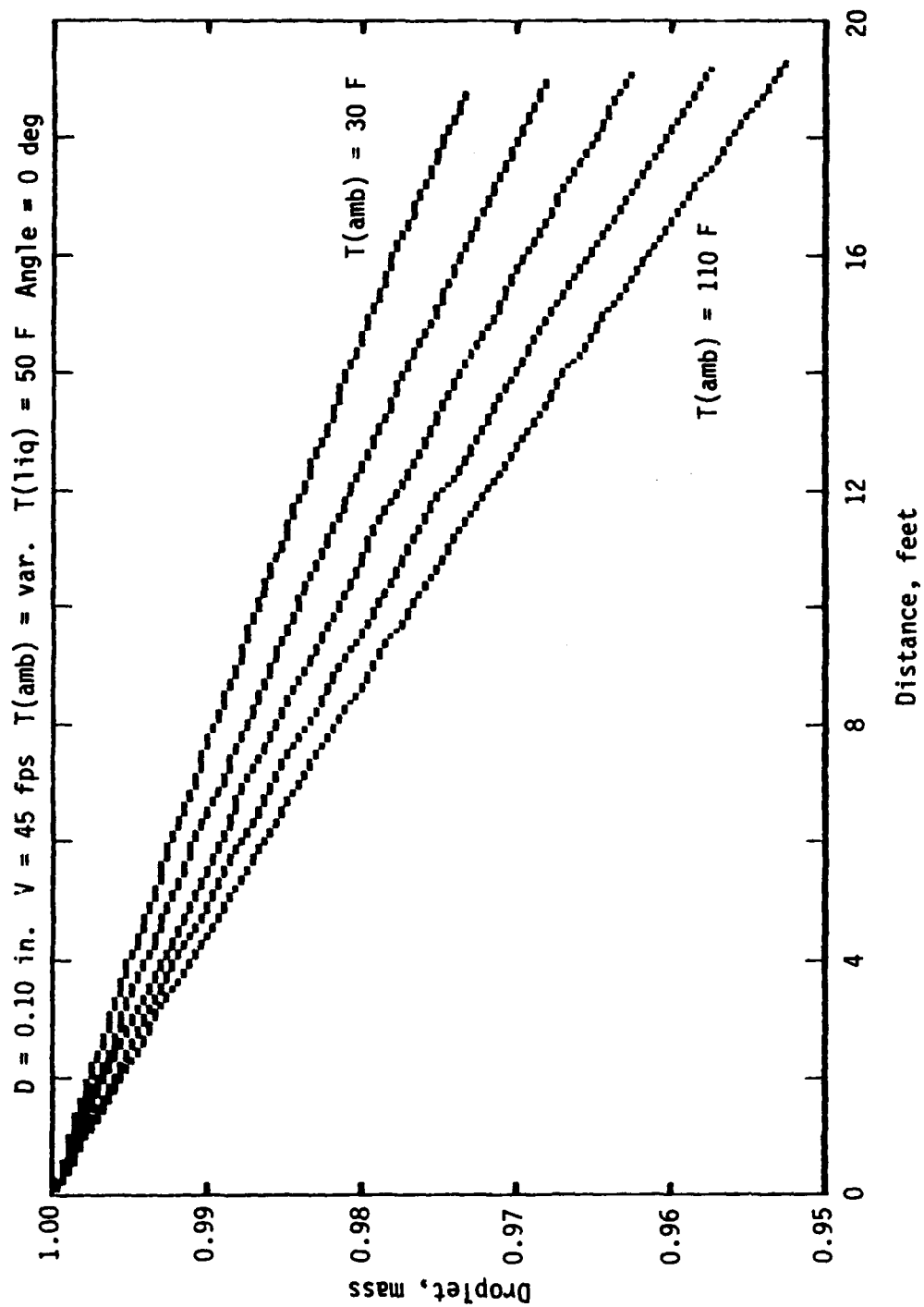
Figure 35. Effect of Ambient Temperature on Calculated Mass Loss for Drop Diameter of 0.10 inch; Velocity of 45 ft/s; Ambient Temperatures of 30 °F, 50 °F, 70 °F, 90 °F, and 110 °F; Liquid Temperature of 50 °F; and Initial Angle of 0 degrees.

D = 0.10 in. V = 45 fps T(amb) = 70 F T(liq) = var. Angle = 0 deg
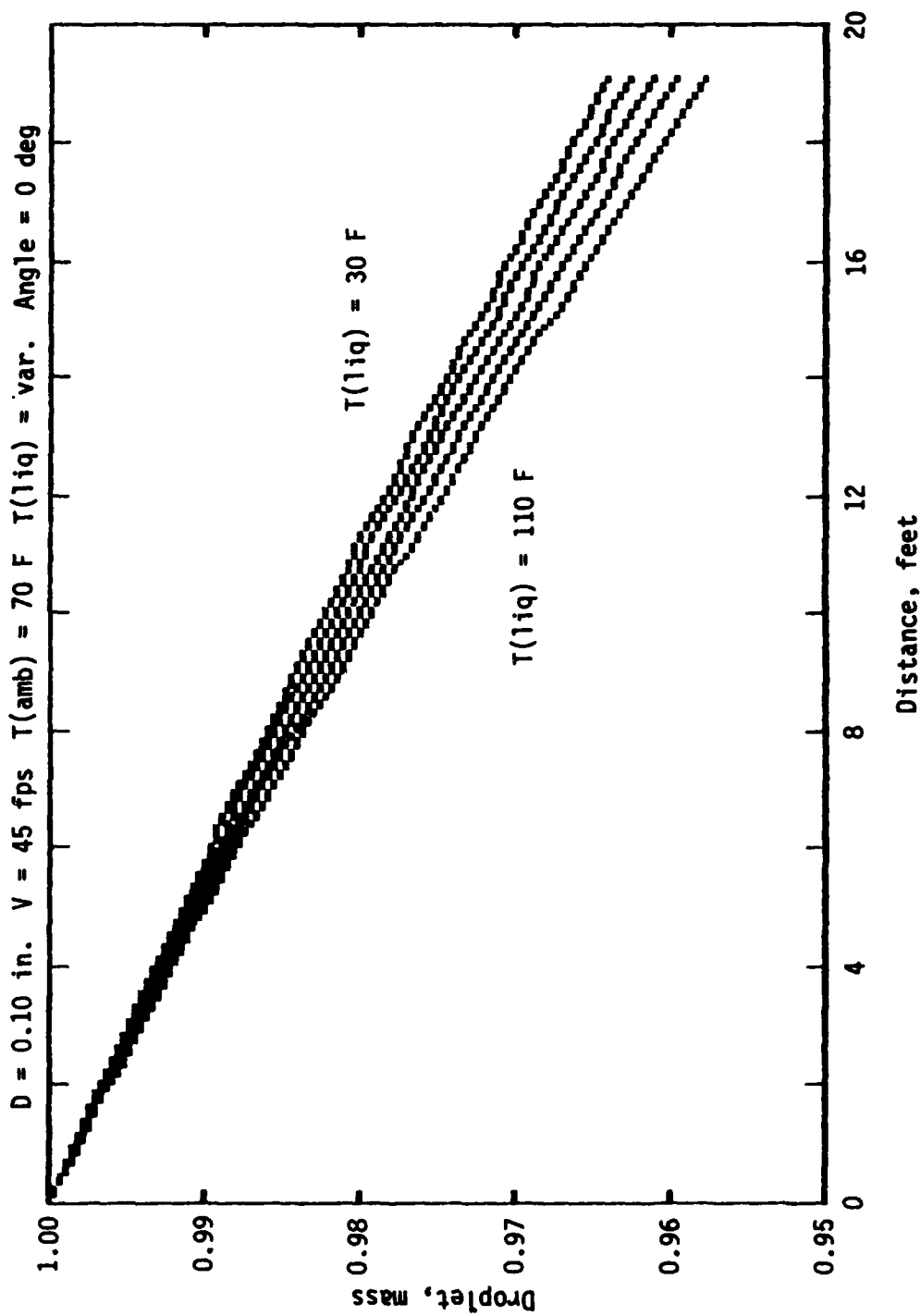
Figure 36. Effect of Liquid Temperature on Calculated Mass Loss for Drop Diameter of 0.10 inch; Velocity of 45 ft/s; Ambient Temperature of 70 °F; Liquid Temperatures of 30 °F, 50 °F, 70 °F, 90 °F, and 110 °F; and Initial Angle of 0 degrees.

The effect of initial velocity on trajectory (Figure 37) and mass loss (Figure 38) is not unexpected. Owing to frictional losses, there is a diminishing return in range for increases in droplet velocity; however, even at the large nozzle velocity of 95 ft/s, the range increases nearly proportional with velocity. The data indicate that a larger nozzle velocity can give the same range as a steeper angle but with a lower mass loss. Figure 38 demonstrates that, for a given distance traveled, evaporative losses decrease significantly with increasing velocity. A change in velocity from 25 ft/s to 95 ft/s decreases the evaporative mass loss from 3.0 percent to 1.4 percent at a distance of 11 feet.

These computer results indicate that optimum deliverability is obtained with drop diameters at or above 0.20 inch and with nozzle angles near 30 degrees. Of course, the absence of any drop formation will give the best delivery (though, not necessarily, the best extinguishment). Ambient and liquid agent temperatures have relatively minor effects on delivery of Halon 2402.

Increasing the nozzle velocity is a better way to increase range than is increasing the nozzle angle, as long as this can be done with no change in drop size since higher nozzle angles give larger evaporative losses. To determine whether this is feasible, the average drop diameter for various velocities in air can be estimated from the equation of air friction atomization developed by Nukiyama and Tanasawa (Reference 20).

$$D = [(0.585/V)(\sigma/\rho)^{1/2}] + 597[\mu/(\sigma\rho)^{1/2}]^{0.45}[1000Q_L/Q_A]^{1.5} \quad (3)$$

Here, D is the average drop diameter, microns; V = relative velocity between gas and liquid, m/s; σ = surface tension, dynes/cm; ρ = liquid density, g/mL; μ = liquid viscosity, poise; Q_L = volumetric liquid flow rate; Q_A = volumetric gas flow rate. A BASIC computer program, "DROP" (Table 23), has been written to calculate the maximum drop size possible for various air velocities. For
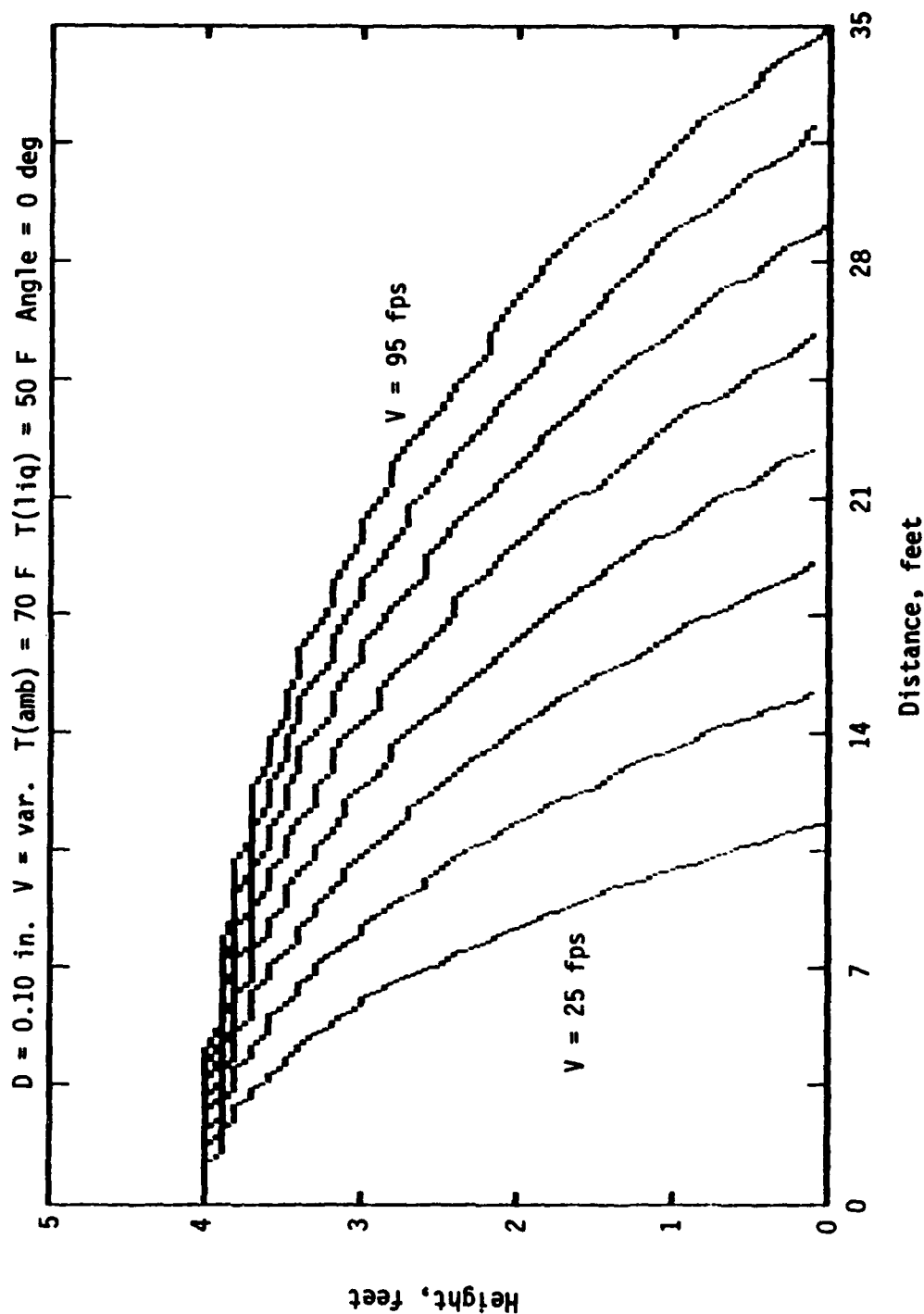
Figure 37. Variation of Calculated Trajectory With Changes in Initial Velocity for Drop Diameter of 0.1 inch; Velocities of 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, and 0.95 ft/s; Ambient Temperature of 70 °F; Liquid Temperature of 50 °F; and Initial Angle of 0 degrees.
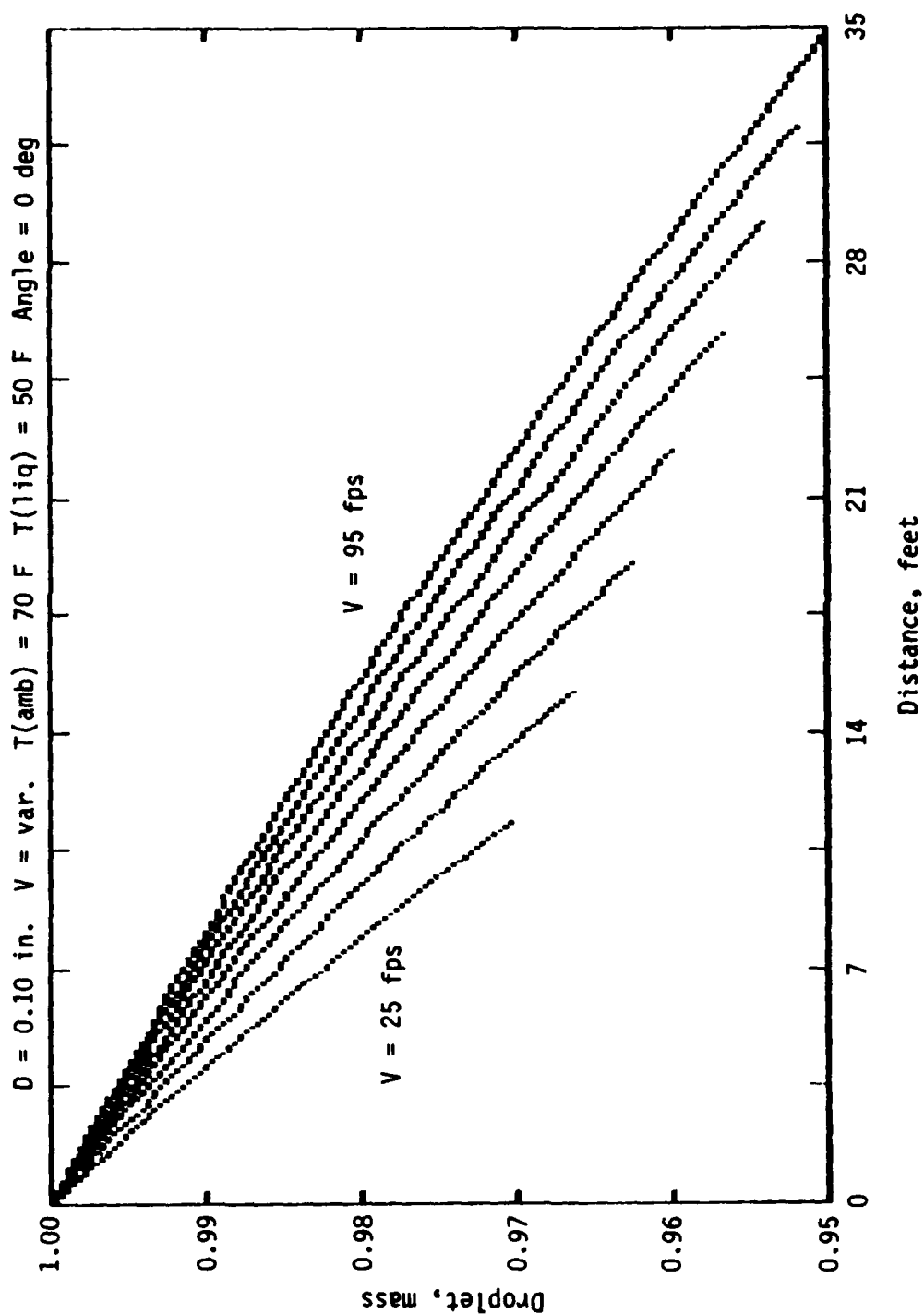
Figure 38. Variation of Calculated Evaporation Rates With Changes in Initial Velocity for Drop Diameter of 0.1 inch; Velocities of 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, and 0.95 ft/s; Ambient Temperature of 70 °F; Liquid Temperature of 50 °F; and Initial Angle of 0 degrees.

TABLE 23.   LISTING FOR BASIC COMPUTER PROGRAM "DROP."

```
10          'DIMENSION/INITIALIZE VARIABLES
20          'DO = AVERAGE SPECIFIC SURFACE DROP SIZE,MICRONS
30          'DOIN = DO IN INCHES
40          'ST = SURFACE TENSION, DYNES/CM
50          'LD = LIQUID DENSITY, G/C.C.
60          'LV = LIQUID VISCOSITY, POISES
65          'V = RELATIVE VELOSITY BETWEEN LIQUID AND GAS
66          'VF = V IN FEET
68          'QL = VOLUMETRIC LIQUID FLOW RATE
70          'QA = VOLUMETRIC GAS RATE
75          'O = QL/QA
80          LV = .0072
85          DO = 0
88          J = 1
89          DIM J (20)
90          ST = 18.9
95          V = 0
100         LD = 2.163
105         DIM DO(20),DOIN(20)
106         OPEN "O",1,"ONE"
110         INPUT "VOLUMETRIC LIQUID FLOW RATE / VOLUMETRIC GAS RATE (QL/QA)?",O
120         FOR VF = 10 TO 200 STEP 10
125         V = (((VF*12)*2.54)/100)
140         DO(J) = ((585*SQR(ST))/(V*SQR(LD))) + (597*((LV/SQR(ST*LD)) .45))*
            ((1000*O) 1.5)
150         J = J+1
160         NEXT VF
165         VF = 10
170         FOR I = 1 TO 20
180         DOIN(I) = DO(I)*3.937E-05
191         LPRINT "RELATIVE VELOCITY BETWEEN AIR AND GAS (F/S)",VF
192         LPRINT "AVERAGE SPECIFIC SURFACE DROP SIZE (INCHES)",DOIN(I)
194         WRITE #1,VF,DOIN(I)
210         VF = VF+10
220         NEXT I
225         CLOSE
230         END
```

Halon 2402, μ = 0.0072 poise at 77 °F, σ = 18.9 dynes/cm at 68 °F (a good estimate for 77 °F), and ρ = 2.163 g/mL at 77 °F. Calculations were carried out for Q_L/Q_A values between 0.05 and 0.001 and for velocities from 10 to 200 ft/s. Selected results are presented in Table 24 and are plotted in Figure 39. For comparison, data for water were calculated and are also presented in Table 24 and in Figure 40.

TABLE 24. AVERAGE CALCULATED HALON 2402 DROP SIZE AS A FUNCTION OF VELOCITY.

Relative air/liquid velocity ft/s	Average drop size, inch			
	Q_L/Q_A = 0.03	0.02	0.01	0.001
Halon 2402				
10	0.204	0.121	0.057	0.023
50	0.186	0.103	0.039	0.005
100	0.184	0.101	0.037	0.003
200	0.183	0.100	0.036	0.002
Water				
10	0.241	0.160	0.098	0.065
50	0.189	0.109	0.047	0.014
100	0.183	0.102	0.040	0.007
200	0.180	0.099	0.037	0.004
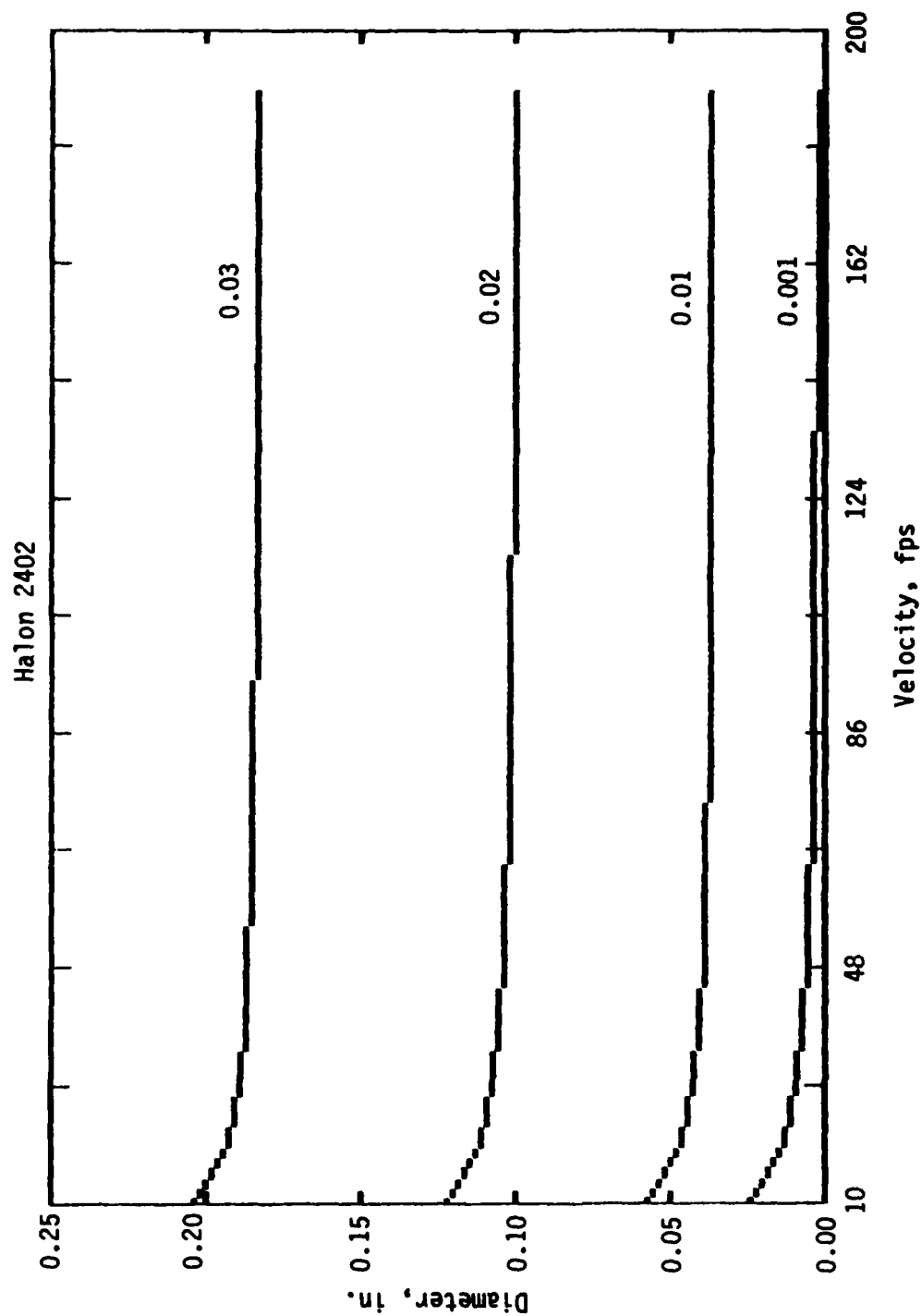
Figure 39. Calculated Average Drop Size for Halon 2402 in Air as a Function of Velocity for Liquid/Air Volume Flow Ratios (Q_L/Q_A) of 0.03, 0.02, 0.01, and 0.001 at 77°F.
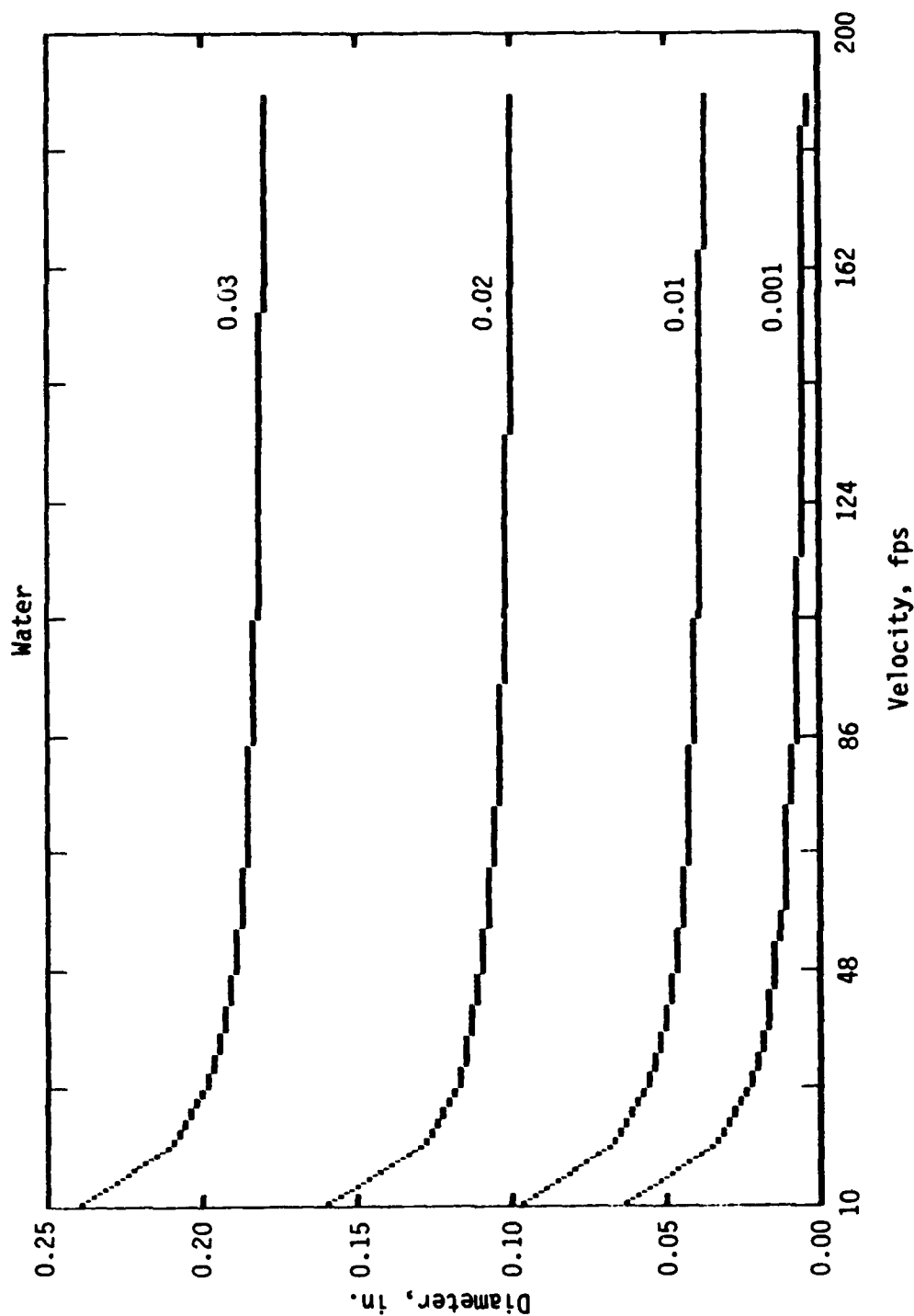
Figure 40. Calculated Average Drop Size for Water in Air as a Function of Velocity for Liquid/Air Volume Flow Ratios (Q_L/Q_A) of 0.03, 0.02, 0.01, and 0.001 at 77 °F.

The average drop size depends on the relative volumes of air and halon in the stream (Table 24). At very high air volumes and large flow velocities, a limiting value of about 0.001-inch diameter is reached. When the amount of air is more limited, large droplets can be maintained, even at large flow rates. These data show that it is possible to use high flow rates if the amount of air introduced into the stream is limited. Once the stream has broken up so that the ratio of Halon 2402 to air becomes small, the average drop size decreases. Drop sizes above 0.05 inch are attainable for liquid Halon 2402 at very low flow rates or for less mixing of halon and air.

Inspection of the data in Table 24 shows that the average drop size for Halon 2402 is less than that for water at lower velocities under these conditions. This is primarily due to the higher density and lower surface tension for Halon 2402. At higher velocities, the right side of Equation 51 predominates and the difference in properties is less important.

5. Conclusions

a. The maximum delivery range for Halon 2402 is obtained with drop sizes of 0.20 inch or above.

b. To prevent evaporative losses upon delivery, range is best increased by increasing nozzle velocity rather than nozzle inclination if this can be done without producing unacceptably small drops.

c. Under the same conditions of flow rate and nozzle design, Halon 2402 will give a smaller average drop size than water.

d. For the same distance traveled and the same drop size, mass losses owing to evaporation decrease with increasing velocity.

e. For a rule-of-thumb estimate, the mass loss per second of travel is 7 percent for a drop size of 0.10 inch and decreases with larger drops. Evaporation losses for streams composed of drops having a diameter of 0.10 inch and smaller are significant.

f. The estimated maximum evaporative losses for solid streams is 0.02 percent per second of travel. For such streams, evaporation losses are negligible for reasonable fire scenarios.

g. Evaporative losses do not increase markedly with liquid or ambient temperatures.

C. FLUID FLOW

1. Objectives

To properly size pipes, to determine nozzle characteristics, and to develop agent delivery apparatuses, properties affecting flow must be known. An important flow property is viscosity. At low temperatures, viscosity can become particularly critical. For Halon 2402, however, measured viscosities at very low temperatures have not been reported though some extrapolated values down to -4 °C (25 °F) have been given (Reference 4). An extension of this range is provided by a study of viscosity as a function of temperature. This permits a determination of the effect of temperature on flow and effectiveness of Halon 2402. The temperatures considered are those which could be encountered by this agent. This section concludes with a discussion of the flow characteristics of Halon 2402.

2. Experimental

Halon 2402 viscosity was determined with a Brookfield Model LVTD viscometer as a function of temperature to below -50 °C (-58 °F). Since the interest is in the viscosity of Halon 2402 at very low temperatures, rather than the absolute viscosity at room temperature, the viscometer was calibrated against Halon 2402 itself (viscosity = 0.72 centipoise [cP] at 25 °C). This procedure permits precise measurements of the temperature dependence, the data of primary concern here. Calibrations against water, which has a reported viscosity of 1.00 cP at 20 °C (68 °F, Reference 21), give values about 1.1 cP too high. The reason for this discrepancy is not known. The Halon 2402 viscosity results are presented in Table 25 and are shown graphically in Figure 41.

TABLE 25. VISCOSITY OF HALON 2402.

Temperature, °C	Viscosity, cP	Temperature, °C	Viscosity, cP
-51.3	3.8	-12.3	1.4
-48.1	3.6	-9.1	1.2
-44.8	3.6	-6.7	1.0
-43.0	3.2	-5.0	1.0
-36.2	3.1	-1.3	0.9
-29.1	2.2	0.7	0.9
-28.9	2.0	2.8	0.8
-24.0	2.0	3.9	0.8
-21.3	1.8	5.7	0.8
-19.4	1.7	6.7	0.8
-17.0	1.5	8.8	0.8
-14.4	1.4	13.3	0.8
		15.3	0.7

3. Discussion

Viscosity can be measured either as absolute viscosity, with poise being one possible unit, or as kinematic viscosity, with stoke (st) as a possible unit. Kinematic viscosity is equal to absolute viscosity divided by density. The kinematic viscosity of Halon 2402 down to -4 °C (25 °F) has been reported from a linear extrapolation of a very small range of data collected at higher temperatures (Reference 4). Viscosity is not generally linear with temperature, as shown in Figure 41, and linear extrapolations are highly suspect. The data determined in the present study can be fit with the non-linear function

$$\mu = 0.9215 - 2.536 \times 10^{-2} \, T(^\circ C) + 6.693 \times 10^{-4} \, T(^\circ C)^2 \qquad (4)$$

for viscosity, μ, in centipoise. For temperature in degrees Fahrenheit,

$$\mu = 1.584 - 2.731 \times 10^{-2} \, T(^\circ F) + 2.066 \times 10^{-4} \, T(^\circ F)^2 \qquad (5)$$
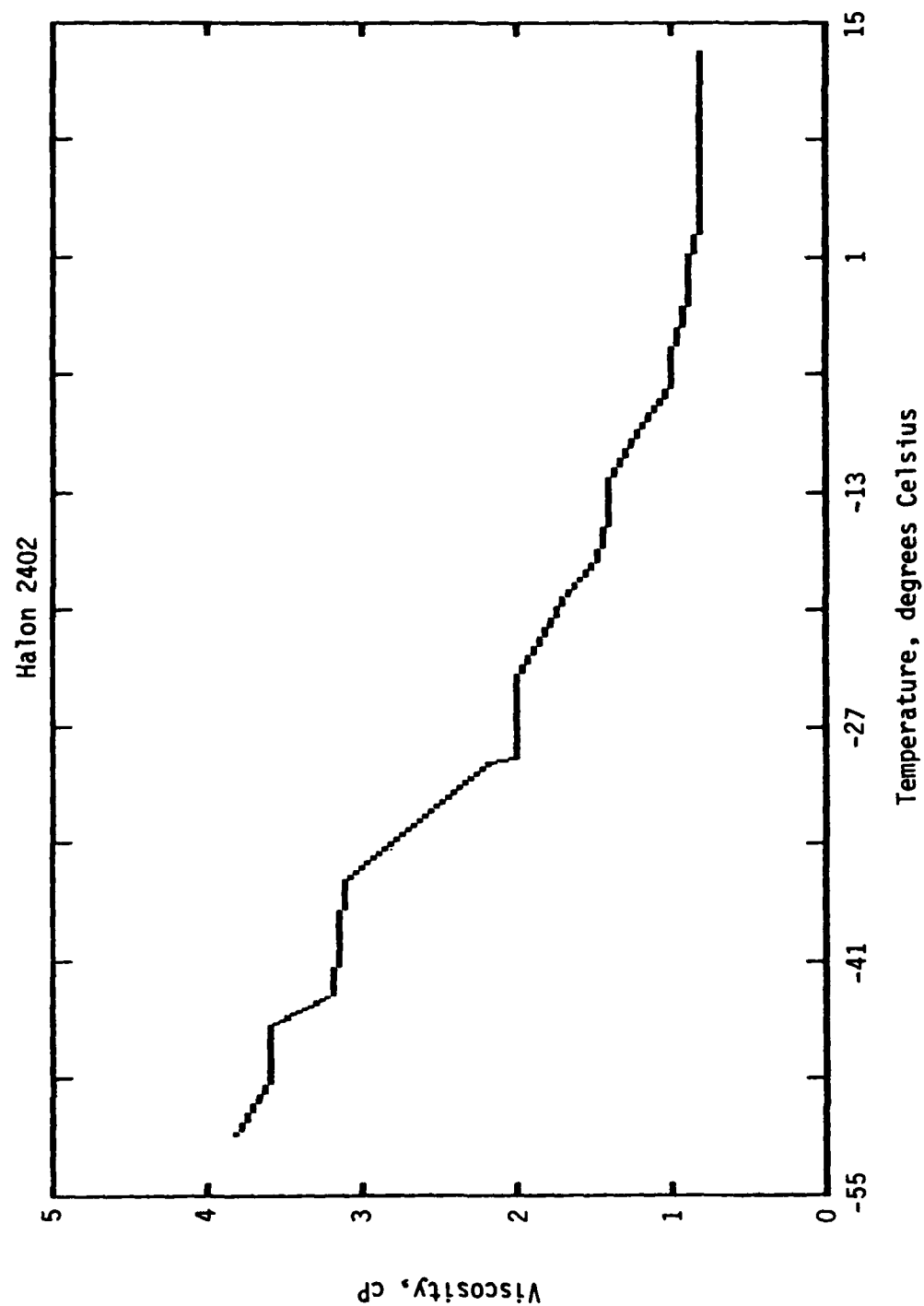
Figure 41. Viscosity of Halon 2402 as a Function of Temperature.

113

Plots of $\log_{10}$ (viscosity) against $\log_{10}$ (absolute temperature) are usually linear (Figure 42). Logarithms of the data from the present study can be fit to the function

$$\log_{10}(\mu, cP) = 17.35 - 7.130 \log_{10}(T, °K) \qquad (6)$$

The data show that even at exceptionally low temperatures, below -50 °C (-58 °F), the viscosity of Halon 2402 is relatively low. At room temperature, the viscosity is less than that of water.

An important parameter for characterizing flow is the Reynolds Number, N_R. For flow of a fluid of viscosity μ and density ρ through a circular pipe of diameter D,

$$N_R = DV\rho/\mu \qquad (7)$$

As the temperature decreases, both the density ρ and the viscosity μ increase; however, the latter decreases much faster than the former. The temperature dependence of the density (Figure 43) can be determined from reported graphed data (Reference 22) to obtain the equations

$$\rho(g/mL) = 2.241 - 2.843 \times 10^{-3} \, T(°C) - 1.531 \times 10^{-5} \, T(°C)^2 \qquad (8)$$

and, in English units,

$$\rho(lb/ft^3) = 142.7 - 8.122 \times 10^{-2} \, T(°F) - 2.829 \times 10^{-4} \, T(°F)^2 \qquad (9)$$

The temperature-dependence of the Reynolds Number can now be determined by combining Equations (7) (with D in meters and V in m/s) and (8). Although at 25 °C (77 °F), the viscosity of Halon 2402 is 28 percent less than that of water, the density (2.163 g/mL) is more than twice as high. Thus the Reynolds Number will be higher for Halon 2402, around 25 °C (77 °F, approximately room temperature), than for water. Since the transition from laminar to turbulent flow occurs in the range N_R = 2000 to 3000, Halon 2402 will tend to
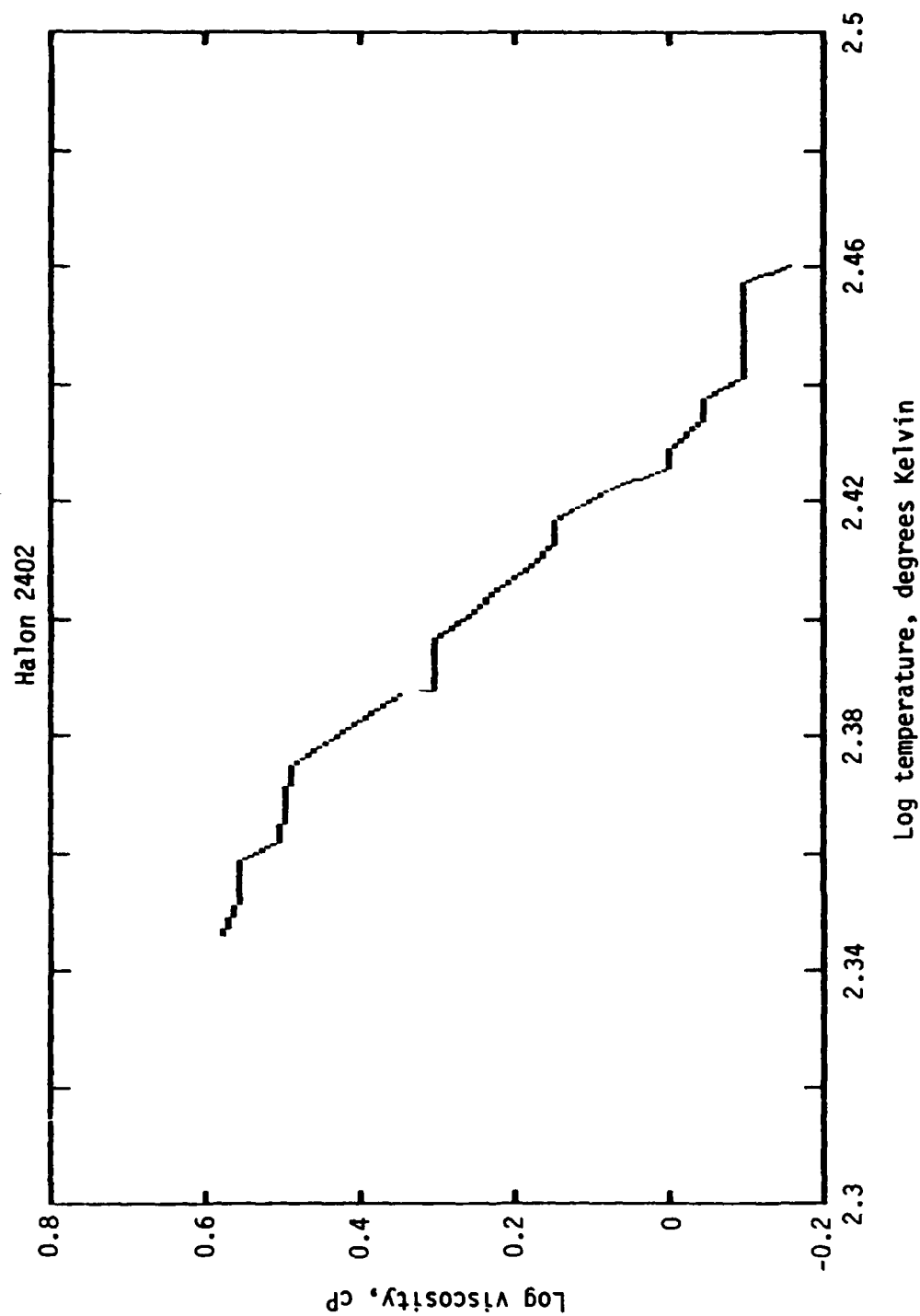
Figure 42. Logarithm of Halon 2402 Viscosity as a Function of Logarithm of Absolute Temperature.
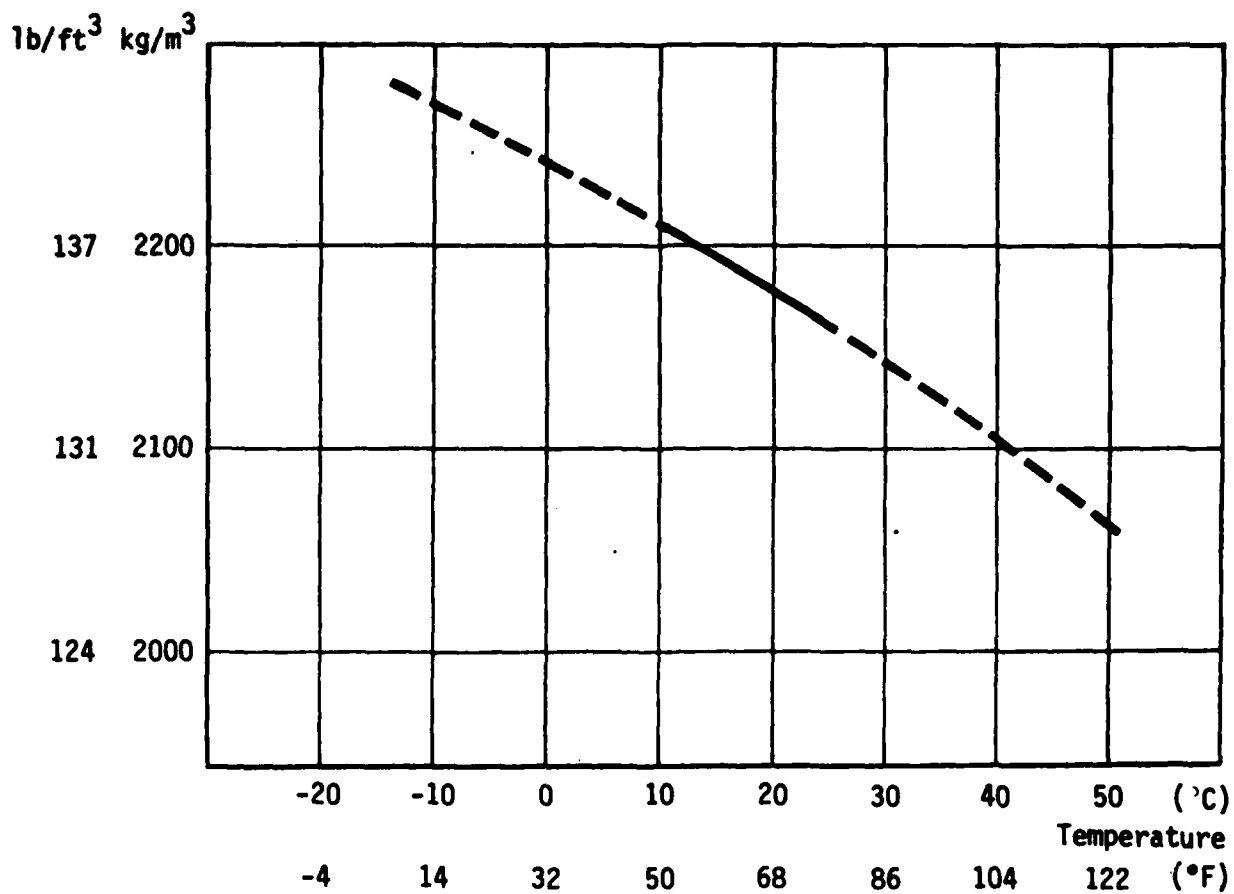
Figure 43. Temperature-Dependence of Halon 2402 Density (Courtesy of Montedison S.p.A., Italy).

become turbulent at pipe diameters about half those where water flow becomes turbulent around room temperature. An alternative way to look at this is that at room temperature, Halon 2402 flow will become turbulent at linear flow velocities about half those of water flow. Note, however, that for nearly all operating conditions in manual and fixed fire suppression systems, Halon 2402 flow will be turbulent. For even a relatively low velocity of 13.7 m/s (45 ft/s) and a relatively small 1.27 cm (1/2-inch) pipe, the Reynolds Number for Halon 2402 at 25 °C (77 °F) is 5 x 10^5.

At lower temperatures, the Reynolds Number for Halon 2402 will decrease owing to the increase in viscosity. By the time the temperature reaches -50 °C (-58 °F), the Reynolds Number for Halon 2402 will decrease to less than one-fifth its value at room temperature for a given set of flow parameters. Even at these low temperatures, laminar flow will occur only for exceedingly small pipe diameters and/or flow rates.

The pressure drop Δp for a fluid of density ρ flowing through a circular pipe of length, L, and diameter, D, at a flow velocity of V can be calculated from the following equation (Reference 23).

$$\Delta p = -\rho[\Delta Z + (V^2/g)(2fL/D)] \tag{10}$$

In English units,* p is in lb/ft^2, ρ is in lb/ft^3, Z is the pipe elevation in feet, g is the standard gravitational constant (32.174 ft/s^2), V is the average velocity in ft/s, and f is the dimensionless friction factor. The pipe dimensions, L and D, must be expressed in feet. There are two parameters of interest in this equation. The first is the ρ term to which the pressure drop is directly proportional. For a given value of f, with all other conditions

---

* Calculations of pressure drops for fluid flow through pipes are universally performed in English units.

being constant, the pressure drop for Halon 2402 in a given situation will be more than twice that of water. The second parameter of interest is f, which, for turbulent flow, is given by (Reference 24)

$$f = 0.00140 + 0.125(N_R)^{-0.32} \tag{11}$$

and for the unlikely case of laminar flow, by

$$f = 64/N_R \tag{12}$$

For turbulent flow, f depends on $N_R^{-0.32}$ and, therefore, the slight decrease in pressure drop (in comparison with water) due to f will be more than offset by the increase due to ρ. Note that for turbulent flow, the temperature dependence of pressure drop is much less than that of viscosity owing to the $N_R^{-0.32}$ term. For example, an increase in viscosity by a factor of 5 causes an increase of only 1.7 in f and in Δp for a negligible first term in Equation (11).

For laminar flow, Equation (7) becomes

$$\Delta p = -\rho\Delta Z + (V^2/g)(2\rho L/D)(64/N_R)$$

$$= -\rho\Delta Z + (V^2/g)(2\rho L/D)(64\mu/DV\rho)$$

$$= -\rho\Delta Z + 128VL\mu/gD^2 \tag{13}$$

Thus, for laminar flow, the high density of Halon 2402 affects the pressure drop only when there is an elevation change. Since the viscosity of Halon 2402 is less than that of water at the same temperature ($\mu_{2402}/\mu_{water} \approx 0.72$ at 25 °C), the pressure drop in pipes with laminar flow and no elevation change will be less than that for water under the same conditions (about 28 percent lower). As the temperature decreases, the pressure drop for laminar flow increases significantly, increasing by a factor of 5 between 25 °C (77 °F) and -50 °C (-58 °F).

Log/log plots of Equation (7) for $\Delta Z = 0$ and f = constant are linear.

$$\log \Delta p = -\log(2\rho fL/gD) - 2\log(V) \tag{14}$$

The slope for such plots is 2.0 regardless of the units used in Equation (7). The value of the constant, $\log(2\rho fL/gD)$, on the other hand, does depend on the units used. Note that these log/log plots will be the same as those for water except for the constant term. A log/log plot for pressure drops in pipes carrying Halon 2402 is shown in Figure 44 (Reference 4).

The thrust due to the large density of Halon 2402, is another flow characteristic of importance since this affects the handling of handlines by personnel and the equipment life. The force due to an open jet of liquid of flow velocity V, mass flow rate W, and density ρ flowing from a pipe of radius r is given by

$$F = VW = \Pi r^2 V^2 \rho \tag{15}$$

Owing to the larger density of Halon 2402, hoses and pipes discharging Halon 2402 will experience forces about twice those due to water. On the other hand, the higher density will double the inertia (resistance to acceleration) of filled pipes and hoses; this will moderate pipe and hose movement. Even so, personnel will experience increased handline thrust with Halon 2402 compared to water. Stress on pipes at bends and corners in Halon 2402 systems will be approximately twice those in water systems under the same conditions.

4. Conclusions

    a. At 25 °C (77 °F), the viscosity and density of Halon 2402 are respectively 28 percent and 216 percent those of water. These differences cause a lower pressure drop for Halon 2402 compared to water for laminar flow (where viscosity is the controlling factor) and a higher pressure drop compared to water for turbulent flow (where density controls). Since Halon 2402 flow will nearly always be turbulent, increased pressure drops should be expected for this agent.

119

Pressure drop

$\frac{lb/}{in^2/ft}$ $kg/m^2/m$
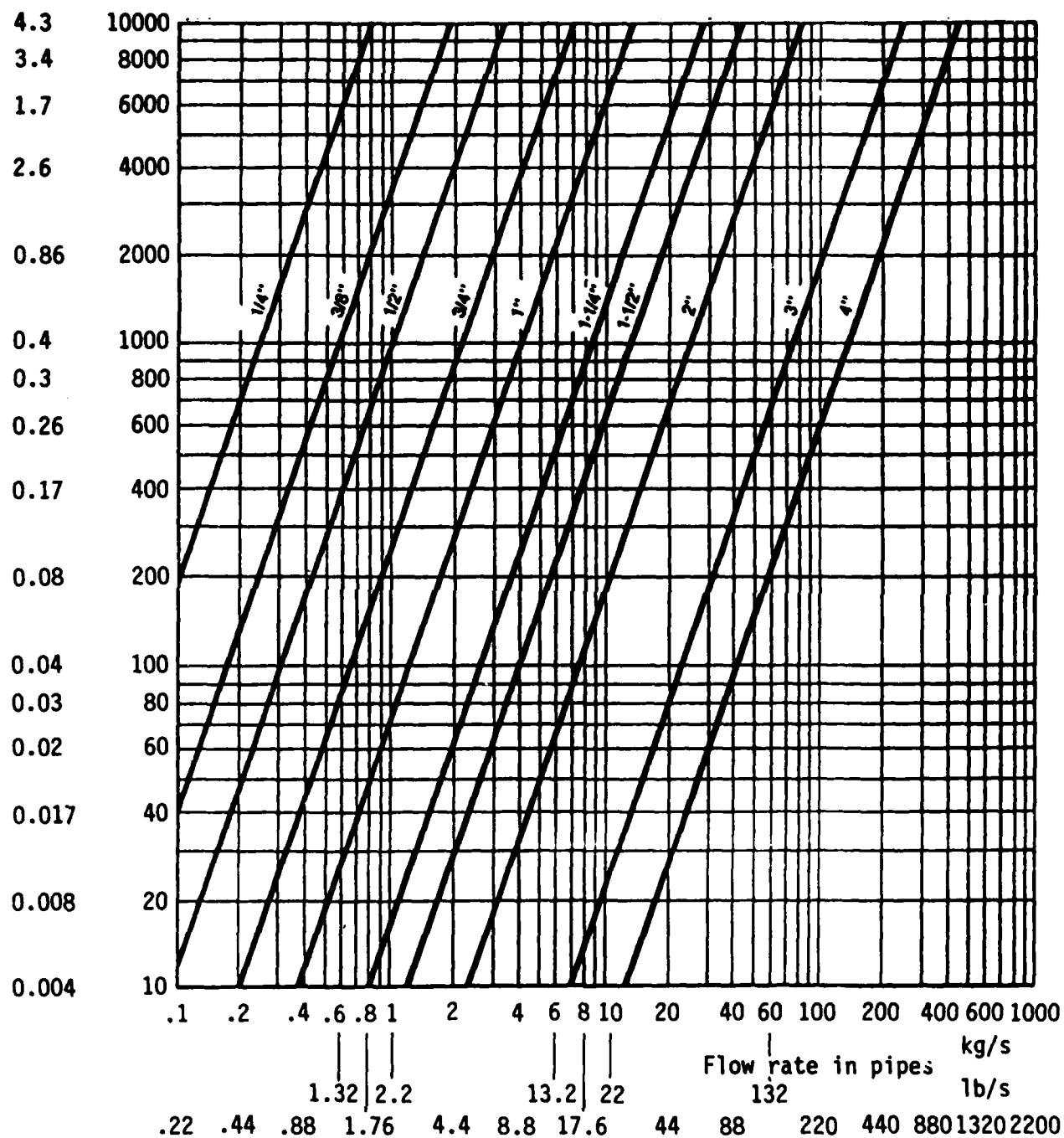
Figure 44. Halon 2402 Pressure Drop in Piping (Courtesy of Montedison S.p.A., Italy).

120

b. Between 25 °C (77 °F) and -50 °C (-58 °F), the viscosity of Halon 2402 increases approximately fivefold. In laminar flow, the pressure drop in pipes over this range will increase by the same factor. For turbulent flow, the pressure drop will increase by a factor of 1.7 for the same viscosity change.

c. The high density of Halon 2402 increases stress due to thrust in pipes, valves, and other system components. Motion will be moderated by increased momentum; however, there may still be some safety problems. Halon 2402 systems must be built to withstand increased thrust.

d. Equations (4), (5), (6), and (10) give the temperature-dependence of viscosity for Halon 2402; Equations (8) and (9) give the temperature-dependence of the density; and Figure 44 gives the Halon 2402 pressure drop in pipes. These equations and the figure can be used as aids in component design.

D. MATERIAL COMPATIBILITY

1. Objectives

Proper use of Halon 2402 requires knowledge of its compatibility with structural materials. This information may be used in the design of containers, piping, valves, nozzles, and other system components as well as in avoiding loss or damage. A variety of polymers, elastomers, and metals have been tested for compatibility with Halon 2402 (References 1, 4, 5, 25). This work is reviewed in this unit.

2. Experimental

ASTM Test D543-67 has been employed to determine material compatibility (Reference 25). Weight, dimension (length, thickness, width), and hardness changes were monitored for eight plastics (Delrin, polyvinylchloride [PVC], nylon, polymethylmethacrylate [PMM], low-density polyethylene [LDPE], high-density polyethylene [HDPE], polycarbonate, and Teflon) and for five rubber elastomers (neoprene, butyl, buna, silicone, and Viton) in contact with Halon 2402. Hardness was determined using a durometer according to ASTM Test

D2240-75. All polymeric materials were tested as 25.4 by 76.2 mm (1- by 3-inch) strips cut from nominal 3.49 mm (1/8-inch) thick sheet stock. Three samples of each polymer were tested. The plastics were allowed to sit for 57 days and the elastomers for 67 days, except for Viton, which was allowed to age for 69 days. Single measurements of weight and length and multiple measurements at different locations of thickness (three locations), width (two locations), and hardness (five locations) were performed on each sample before and after aging. A separate closed container was employed on each strip tested. The results are given in Table 26.

Of the plastics, PVC, polycarbonate, Delrin, and nylon exhibit the smallest changes in dimensions. Polymethylmethacrylate exhibits severe degradation. All of the rubber elastomers show large changes in properties and dimensions. Neoprene is the best of the elastomers and Viton is the worst. Silicone appears better than it is, owing to the shrinkage that occurred before measurement.

One Halon 2402 manufacturer has reported (Reference 4) the measurements and conclusions on compatibility presented in Table 27.

The results and conclusions in this table are suspect. For example, polymethylmethacrylate is reported to be compatible; however, in the Reference 23 study, this polymer decomposed. Moreover, both dimensional and weight changes, rather than just the latter, should have been monitored in the Reference 4 study.

The DuPont Company has determined the elastomer swelling data reported in Table 28 (Reference 26). The results are for room temperature; however, the aging time is not reported, nor is the method of determining the swelling percent. Data for other halons are shown for comparison.

TABLE 26. PROPERTY CHANGES OF POLYMERS IN CONTACT WITH HALON 2402.[a]

Polymer	Hardness[b] change	Change, percent			
		Weight	Length	Thickness	Width
Delrin	-0.4(8)	0.22(1)	0.01(1)	-0.5(5)	-0.07(4)
PVC	-0.2(6)	-0.02(0)	0.02(1)	0.5(10)	0.07(10)
Nylon	3.3(12)	0.12(1)	0.00(0)	0.3(5)	0.07(8)
PMM	0.49(9)	[c] ---	[c] ---	0.3(6)	-0.10(7)
LDPE	-4.2(12)	14.38(2)	1.96(5)	2.1(7)	1.65(5)
HDPE	-3.4(7)	9.15(10)	1.39(1)	1.7(5)	1.10(10)
Polycarbonate	-1.3(8)	-0.01(1)	0.03(0)	0.0(7)	0.02(6)
Teflon	-5.3(8)	3.90(136)	0.41(1)	3.2(9)	0.52(6)
Neoprene	8.9(8)	4.92(152)	-3.68(20)	-8.2(3)	-3.89(31)
Butyl	-7.0(8)	48.76(26)	3.69(3)	7.1(5)	4.49(19)
Buna	-15.4(28)	42.90(222)	1.74(18)	[d] ---	2.05(12)
Silicone[e]	-2.2(7)	-3.66(11)	-1.44(8)	-3.2(4)	-1.12(9)
Viton	-14.0(9)	25.0(1)	4.0(16)	8.1(4)	6.9(45)

[a]Reference 25. Average deviations of last significant digit are given in parentheses.

[b]A Type D durometer was used for the plastics and a Type A durometer for the rubber elastomers.

[c]Polymethylmethacrylate breaks into pieces in Halon 2402.

[d]No thickness measurement was made for buna owing to pockets of Halon 2402 within the sample after aging.

[e]The silicone rubber sample shrank between the time it was removed from the Halon 2402 and the time of measurement (about 24 hours later). The immediate dimensions upon removal were about 50 percent larger than the dimensions before aging.

TABLE 27. COMPATIBILITY OF HALON 2402 WITH PLASTICS AND ELASTOMERS.[a]

Material	Maximum increase in weight, percent	Compatibility
ABS resins (acrylonitrile-butadiene-styrene copolymer)	140	No
Buna-N acrylonitrile-butadiene rubber	20	Yes
Polymethylmethacrylate	0	Yes
Natural rubber	700	No
Polychloroprene rubber (neoprene)	28	Yes
Polyamide 66 (nylon)	3	Yes
Polyethylene	14	Yes
Polystyrene	Dissolves	No
Algoflon PTFE (polytetrafluoroethylene)	9	Yes
Rigid PVC resins	0	Yes
Tecnoflon fluorinated elastomer	11	Yes
Epoxyphenolic resin (coating)		Yes

[a]Reference 4.

TABLE 28. SWELLING OF ELASTOMERS.[a]

Elastomer	Maximum swelling, percent				
	Halon: 2402	1211	1202	1301	1011
Hycar OR-15	6.8	4.8	11.1	0.6	49.3
Perbunan 26	10.0	10.1	22.9	0	50.4
Neoprene GN-A	6.0	13.0	26.7	0.2	34.1
Hypalon E-7	9.8	7.2	29.0	2.3	40.0
GR-S	15.2	14.6	24.0	1.0	26.0
Natural rubber	24.0	23.4	34.1	1.3	31.5
Butyl	24.0	2.3	47.0	2.0	14.7
Thiokol-PA	4.0	4.1	7.9	0.3	[b]
Silicone 23	33.3	14.9	36.3	21.5	14.4

[a]Reference 26.

[b]Sample disintegrated.

The results in Table 28 permit some rapid comparisons between agents. Of importance to the report is the observation that Halon 2402 is comparable to Halon 1211 in the swelling of elastomers with two exceptions. Halon 2402 causes much larger swellings of butyl and silicone 23 rubbers.

It is difficult to determine at what point a polymer is acceptable. All of the polymers and elastomers tested show some degradation. This is in spite of the statement that "[Halon 2402] does not affect most plastics and elastomers" (Reference 4). Very long-term testing to include stress-strain and tensile strength analyses and in-service testing may be needed to settle the question of compatibility with plastics and elastomers.

Dry Halon 2402 does not corrode common construction metals. However, in the presence of water, hydrolysis may occur to form acids which can deteriorate the metal. Thus a metal may be compatible with dry Halon 2402 but not with wet Halon. The following recommendations (Table 29) have been made by one Halon 2402 manufacturer (Reference 4). Even if water is not present as a separate phase, limited corrosion can occur owing to hydrolysis of Halon 2402 by dissolved water.

The Purdue Research Foundation has investigated the corrosion of metals by some halons in its pioneering study on agents (Reference 1). In the accelerated tests, polished and weighed strips of the metal and 20 mL of agent were sealed in glass tubes, which were maintained at a temperature of 200 °C for 30 days. The physical conditions of the strips were noted and the strips were reweighed after removal of coatings. A second series of tests was run at 93 °C. The results are shown in Table 30.

An extensive study on the stability of halons has been reported by the DuPont Company (Reference 26). In that investigation, steel, brass, and aluminum test samples were heated with agents. In one series of tests, anhydrous agents were used. In another, 3 percent by volume of water was added to give a separate phase. Agent penetration was determined for sample exposures at 120 °C for 260 days. The results are given in Table 31. Negative values indicate that a tightly adhering coating formed.

TABLE 29. COMPATIBILITY OF METALS WITH HALON 2402.[a]

Metal	No water present in Halon 2402 as a separate phase	Water present in Halon 2402 as a separate phase
Aluminum	Yes	Not advisable
Brass	Yes	Not advisable
Bronze	Yes	Not advisable
Copper	Yes	Yes
Carbon steel	Yes	Not advisable
Stainless steel 316	Yes	Yes
Titanium	Yes	Yes
Tin	Yes	Not advisable

[a]Reference 4.

TABLE 30. CORROSION OF METALS BY HALON 2402 AT ELEVATED TEMPERATURES.[a]

Metal	Initial mass, g	Final mass, g	Mass change, %	Appearance
Temperature, 200 °C				
Copper	1.7443	1.5442	-11	Gray coating
Aluminum	1.4465	0	-100	Completely corroded
Iron	2.9080	2.9043	0.1	Black coating
Temperature, 93 °C				
Copper	1.8852	1.8852	0	No discoloration
Aluminum	1.1781	1.1781	0	No discoloration
Iron	3.4582	3.4582	0	No discoloration
Brass	3.8064	3.8053	0.03	No discoloration

[a]Reference 1.

126

TABLE 31. PENETRATION OF METALS BY HALONS DURING 260-DAY AGING AT 120 °C.

Halon	Penetration, 10^{-6} cm/mo[a]					
	Aluminum		Brass		Steel	
	Anhydrous	Wet	Anhydrous	Wet	Anhydrous	Wet
2402	1.0	127	14.5	978	3.8	356
1301	1.8	150	3.8	-89	2.3	-231
1211	2.0	137	15.2	1105	2.8	208
1202	1.8	140	1.8	953	2.0	157
1011	>3810	>3810	508	4115	68.6	711

[a]Centimeters per month. These values are from Reference 26, which reports penetrations in inches per month.

The proposed standard for Halon 2402 of the National Fire Protection Association (NFPA-12CT Committee), which has since been withdrawn, specifies that ordinary cast-iron or nonmetallic pipe not be used for Halon 2402 (Reference 22). In the case of cast iron, this specification is apparently made owing to stress rather than corrosion considerations.

3. Conclusions

a. In general, Halon 2402 has a material compatibility similar to that of Halon 1211 but considerably worse than that of Halon 1301.

b. Halon 2402 causes some property changes in all plastics and elastomers tested. Such changes are indicative of some degree of degradation. Of all plastics tested, PVC, polycarbonate, Delrin, and nylon show the least degradation. Neoprene and thiokol are the least affected of the rubbers; however, all rubbers exhibit significant swelling.

c. In the absence of water and elevated temperatures, most metals can be used with Halon 2402. In the presence of water, only copper, stainless steel, or titanium should be used.

d. To prevent corrosion, every precaution should be taken to eliminate water from Halon 2402 systems. All drums and equipment must be checked before filling. Careful drying procedures must be employed where necessary.

SECTION IV
SAFETY AND ENVIRONMENT

In this section, the safety and environmental impact of the use of
Halon 2402 are examined. Among the subjects for which data are presented and
discussed are evaporation and dispersion, concentrations of Halon 2402 experi-
enced during use, products of combustion, toxicity, and effect on the
environment.

A. TOXICITY

The health effects of Halon 2402 are of concern in view of the known
ordering of increasing toxicity of Halon 1301 < Halon 1211 < Halon 2402, for
the three most widely used halon fire extinguishing agents. Toxic effects
owing to inhalation of gases involved in the use of halons are of much more
concern than those from other exposure pathways. There are several measures of
the toxicity of a gaseous material (Reference 27).

The LC_N is the Lethal Concentration, N percent kill--the concentration of
gaseous materials which kills N percent of the animals in a group. Normally N
is 50. The units of an LC_N value are usually percent or ppm by volume.

The ALC is the Approximate Lethal Concentration, the approximate
concentration of material which would prove lethal for a given inhalation time.
The ALC values may or may not give a percent kill.

The OSHA PEL value is the Permissible Exposure Limit as defined by The
U.S. Occupational Safety and Health Administration (Reference 28). This is an
8-hour time weighted average unless otherwise stated.

The TLV is the Threshold Limit Value, which gives the upper allowable
concentration limit of a toxic material. These values are established by the
American Conference of Governmental Industrial Hygienists (Reference 29) and
are based on the best available information from industrial experience, experi-
mental animal studies, and human studies. There are three types of TLV.

128

The TLV-TWA is the Threshold Limit Value - Time Weighted Average, the highest permissible average concentration for a normal 8-hour workday and 40-hour workweek. At this concentration and under these conditions, there are no adverse effects.

The TLV-STEL is the Threshold Limit Value - Short-Term Exposure Limit, the concentration to which exposure for a short period of time is possible without serious effects (irritation, tissue damage, or significant narcosis). The TLV-STEL is for a 15-minute exposure which should not be repeated more than four times per day and which should not occur at shorter time intervals than 60 minutes. Often, TLV-STEL values are unknown; however, they can be predicted from the following excursion limit recommendation: "Short-term exposures should exceed three times the TLV-TWA for no more than a total of 30 minutes during a work day and under no circumstances should they exceed five times the TLV-TWA, provided that the TLV-TWA is not exceeded" (Reference 29).

The TLV-C value is the Threshold Limit Value - Ceiling, a concentration that should not be exceeded.

1.   Neat Agent

There are two health effects of halogenated hydrocarbons (Reference 30). First, they can cause Central Nervous System (CNS) responses such as dizziness, impaired coordination, and anesthesia. Second, inhalation of halogenated hydrocarbons can cause cardiac arrythmia and cardiac sensitization to adrenaline. Screening tests on dogs injected with large doses of epinephrine (adrenaline) indicate possible serious arrhythmia after 5 minutes at 1000 ppm of Halon 2402. Cardiac arrhythmias and CNS effects appear to be readily reversible upon termination of exposure; however, both can lead to death with excessive exposure.

Although Halon 2402 is stated to be of "a low toxicological risk" with "no hazards reported under normal handling and operating conditions" (Reference 4), this appears to be an oversimplification of the toxicological properties. In the same document the threshold for CNS effect is reported as 22 g/m^3 (1898 ppm, 0.2 percent by volume). The caution is also given that

inhalation of concentrations exceeding 100 g/m^3 (8627 ppm, 0.9 percent) for time periods exceeding 30 seconds can induce CNS depression and narcosis and should be avoided.

Early work by the United States Army Chemical Corps (Reference 31) indicates an ALC_0 of 126,000 ppm (12.6 percent) for Halon 2402 for white rats exposed for 15 minutes (Table 32). The ALC_0 is the approximate highest concentration giving no mortality. Tests on acute toxicity in Sprague-Dowley male rats with an average weight of 250 grams have been performed by the University of Milan and Montedison (Reference 32). The results give respective ALC_0, ALC_{50}, and ALC_{100} values of 131,600 ppm (13.1 percent, 1.40 kg/m^3), 173,900 ppm (17.4 percent, 1.85 kg/m^3), and 216,200 ppm (21.6 percent, 2.30 kg/m^3) for a 4-hour exposure.

TABLE 32. APPROXIMATE LETHAL CONCENTRATION (ALC) FOR A 15-MINUTE EXPOSURE.[a]

Halon	Undecomposed vapor,		Pyrolized at 800 °C,	
	mg/L	ppm	mg/L	ppm
1301	5075	834,000	86	14,000
1211	2200	324,000	52	7,650
2402	1340	126,000	17	1,600
1202	470	54,000	16	1,850
1011	340	65,000	20	4,000
104	180	28,000	2	300

[a]Reference 31.

Tests have been performed on humans at the Medical College of Wisconsin (Reference 33). No adverse effects were observed for 4-hour exposures at concentrations of 250 ppm (0.025 percent) and 500 ppm (0.050 percent). Men exposed to 1000 ppm (0.10 percent) exhibited no adverse response up to 30 minutes and only minimal CNS response after 60 or more minutes for some subjects. Definite CNS reponses (impaired coordination, dizziness) were observed for all subjects after 2 minutes at 2000 ppm (0.2 percent).

The U.S. Army has adopted the following recommended concentration levels for personnel exposure to Halon 2402 (Reference 34). For concentrations up to 0.05 percent (500 ppm), the *maximum permitted time* of exposure is 10 minutes. For concentrations from 0.05 to 0.1 percent (500 to 1000 ppm), the *maximum exposure time* is 1 minute. Above 0.1 percent (1000 ppm), exposure should be prevented. In the remainder of this report, these standards will be referred to as the U.S. Military recommended levels for inhalation.

Early results in some studies now in progress* indicate that Halon 2402 contaminants may significantly increase agent toxicity.

Halon 2402 toxicity threat by routes other than inhalation are relatively small. A Polish study (Reference 35) has determined oral toxicities for animals. The values, however, are so high (in the g/kg range) as to be essentially meaningless. Accidental oral ingestions of this magnitude would be almost impossible. No research has been conducted on dermal toxicity of Halon 2402. The blood concentration due to whole-body exposure of rats to 3,000 ppm of dibromomethane is equal to that achieved by inhalation of 200 ppm of this compound (Reference 36). The skin absorption of dibromomethane may resemble that of Halon 2402.

2.   Products of Pyrolysis

Halon 2402 exhibits significant pyrolysis (decomposition due to heat) at temperatures above 400 °C (752 °F, Reference 37). Since the average fire temperature is 1100 °C (2012 °F), extensive Halon 2402 decomposition may occur upon agent application. This decomposition is, of course, believed necessary to inhibit the chain reactions and provide extinguishment.

The toxicity of decomposed Halon 2402 is reported to be higher than that of either Halon 1211 or 1301. Probably the most toxic of the pyrolytic decomposition products of any of the halons are the simple halogen-containing ("inorganic") materials - hydrogen halides (HX), free halogens (X_2), and carbonyl halides (COX_2), where X = Cl, Br, or F. Although it has been reported

---

*Humphey, B. J., and Smith B., Toxicity of Halon 2402, Air Force Engineering and Services Center, Tyndall Air Force Base Florida, work in progress.

that free fluorine is not obtained (Reference 5), most of the work in this area is quite old. Until proved otherwise, with modern high precision analytical instrumentation, one should not rule out the possibility of free fluorine. The specific compounds possible for Halon 2402 are hydrogen bromide (HBr), hydrogen fluoride (HF), bromine (Br_2), fluorine (F_2), carbonyl fluoride (COF_2), and carbonyl bromide ($COBr_2$). Chlorine-containing species will be present only to the extent that chlorine-containing impurities are present in the agent. Formations of the mixed-halogen species COBrF and the interhalogen compounds BrF, BrF_3, and BrF_5 are also possible; however, these species are not usually considered in discussions of the toxicity of Halon 2402 decomposition products.

The halogen-containing inorganic products are all highly toxic, corrosive, and irritating materials capable of causing severe lung damage and, in high concentrations, death. The carbonyl halides hydrolyze (react with water including water in air passages) to form hydrogen halides and carbon dioxide. It has been claimed that the "characteristic sharp, acrid odor of decomposition products, even in minute concentrations provides a built-in warning system and encourages people to evacuate the area" (Reference 4). It is primarily these highly toxic, simple, halogen-containing inorganics which have sharp and acrid odors. Pyrolysis products such as carbon monoxide (CO) and most organic halides have mild or nondetectable odors. It must be noted that Halon 2402 is not unique in giving highly toxic halogen-containing inorganics. Other halons also produce such products, and chlorine-containing halons (Halon 1211 for example) give additional highly toxic materials. The toxicities of the inorganic halogen-containing compounds are given in Table 33.

B. EVAPORATION

   1.   Objectives

   Environmental impact and personnel exposure depend on evaporation rates of Halon 2402. In this unit, experimental and computer modeling results on evaporation rates for Halon 2402 are presented. In the laboratory studies, Halon 2402 was permitted to evaporate under various conditions. The computer program developed permits the calculation of evaporation rates as a function of temperature, ground condition, wind, and solar flux. These data permit estimates of vapor concentrations, personnel exposures, and area contamination times from spills.

TABLE 33. TOXICITIES OF HALOGEN-CONTAINING INORGANIC HALON 2402 PYROLYSIS PRODUCTS.

Material	TLV-TWA,[a] ppm	TLV-STEL,[a] ppm	ALC,[b] ppm	OSHA PEL,[c] ppm
Hydrogen fluoride	3[d]	6	2500	3
Hydrogen bromide	3[d]	--	4750	3
Fluorine	1	2	375	0.1
Bromine	0.1	0.3	550	0.1
Carbonyl fluoride	2	5	1500	2
Carbonyl bromide	--	--	100-150[e]	--
Bromine pentafluoride	0.1	0.3[f]	--	--

[a]Reference 29.

[b]Reference 22.

[c]Reference 38.

[d]It is proposed that this be a ceiling limit.

[e]This is the value for carbonyl chloride. A value for carbonyl bromide has not been proposed.

[f]It is proposed that this TLV-TWA value be deleted from the list of recommended limits.

2. Experimental Studies and Results

a. Laboratory Evaporation Study

A tared flat-bottomed Petri dish with a surface area of 62.21 cm^2 and a wall height of 2 cm was filled with Halon 2402 and was placed on a top-loading balance. A sealed enclosure, 44.45 cm (17.5 inches) high by 30.5 cm (12 inches) square, was placed around the balance and a variable-speed air blower was used to pull air across the halon surface. Air velocity and temperature were measured with a hot-wire anemometer. The Halon temperature was monitored with a Type K chromel-alumel thermocouple wire lying just below the surface of the liquid. Tests were conducted for air velocities of 0, 15.2, 30.5, 61.0, and 91.4 m/min. The maximum velocity corresponds to a wind speed of 5.5 km/h (3.4 mi/h). Higher air velocities caused instability in the

apparatus used for these measurements. An initial Halon 2402 mass of 215 grams (volume of 100 mL) was employed in each test. The estimated deviation on the nonzero air velocities is ±3 m/min.

The data obtained from these studies--time, mass, halon temperature, air temperature, and the difference in the two temperatures--are given in Tables D-1 through D-5 in Appendix D. The temperature difference gives a better estimate of temperature lowering as a function of air velocity than does the temperature itself since the air temperature varied slightly within and between the runs. Appendix D also contains graphs of the mass changes (Figures D-1 through D-5), air and Halon temperature variations (Figures D-6 through D-10), and the temperature difference changes (Figures D-11 through D-15) as functions of time for the five experimental runs.

Figure 45, a composite of Figures D-1 through D-5, Appendix D (Volume II), graphically presents the mass losses during the five runs. As expected, the rate of mass loss increases significantly with the air flow velocity. The curves show that the rate of evaporation decreased slightly toward the beginning of each test owing to the initial decrease in the Halon 2402 temperature. Once the liquid temperature reached equilibrium, which occurred within 10 to 15 minutes, the rate was relatively constant, decreasing only slightly owing to wall effects and changes in the bulk heat capacity. Overall mass fluxes* were obtained by eliminating points near the beginning and end of each test. The fluxes obtained and other data are presented in Table 34.

---

* Mass flux is the mass evaporation rate per unit area.
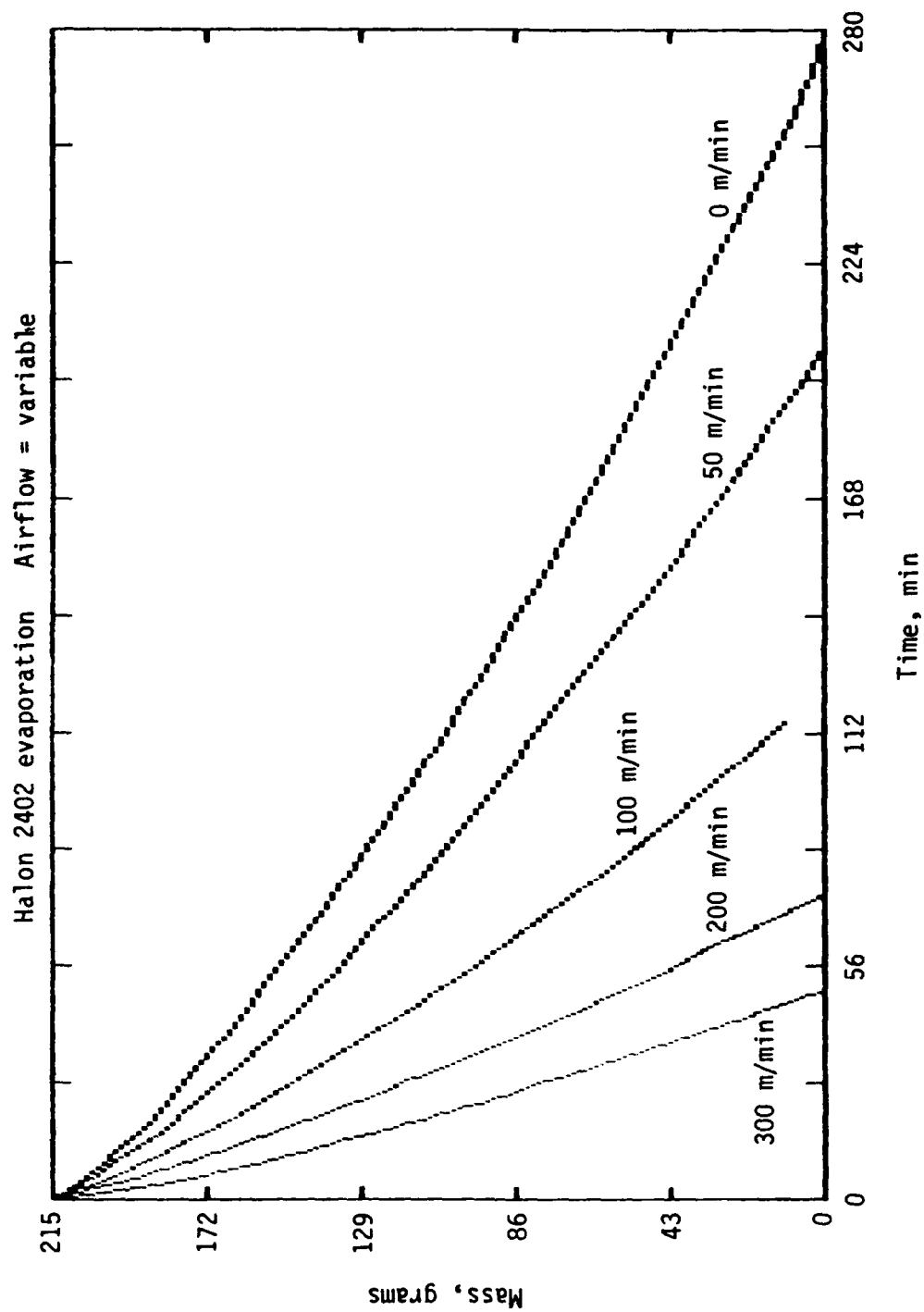
Figure 45. Mass of Halon 2402 as a Function of Time for Evaporation Studies With Air Flow Velocities of 0, 50, 100, 200, and 300 ft/min.

135

TABLE 34. MASS FLUX RATES AND TEMPERATURE DECREASES FOR HALON EVAPORATION.

Air flow rate, m/min	Average air temperature,[a] °C	Equilibrium halon temperature, °C	Temperature lowering, °C	Mass flux rate, g/cm^2/min
0	20.1	12.5	-7.6	0.0125
15.2	20.1	11.1	-9.0	0.0167
30.5	18.2	1.8	-16.4	0.0272
61.0	21.4	-1.4	-22.8	0.0474
91.4	25.4	-1.4	-26.8	0.0646

[a]Estimated from the temperatures at the point at which one-half the halon had evaporated.

The dependence of mass flux rate on air flow velocity is illustrated in Figure 46, a plot of the data in Table 34. Excluding the point at zero air flow, the data are fit well with the least-squares linear function,

$$R = 7.77 \times 10^{-3} + 6.30 \times 10^{-4} V \qquad (16)$$

with R, the mass flux rate, in units of g/cm^2/min and V, the air velocity, in m/min.

The temperature of the evaporating Halon 2402 fell steeply during the first part of each test and then remained relatively constant until most of the liquid had evaporated, at which time it rose sharply (Figures D-6 through D-10, Volume II). The equilibrium liquid and average air temperatures are reported in Table 34. The equilibrium temperature decreases with increasing flow rate. A composite plot of Figures D-11 through D-15, which show the differences between the ambient air and Halon 2402 temperatures as functions of time, is shown in Figure 47. The sharp breaks in the curves show where the liquid had evaporated below the temperature sensor.

Halon 2402 evaporation

Flux, g/min cm²

Air velocity, m/min
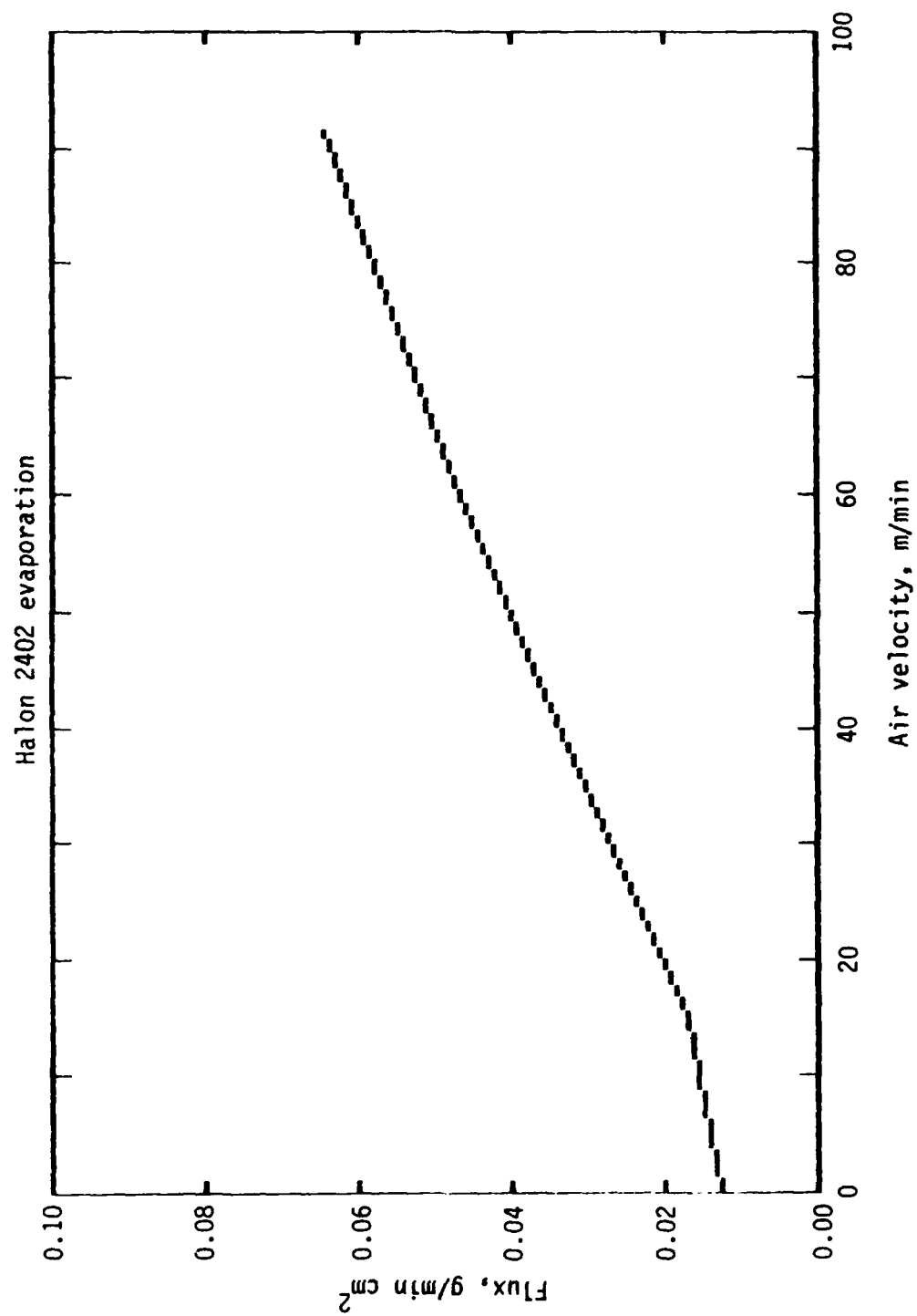
Figure 46. Dependence of Halon 2402 Evaporation Rate on Air Flow Velocity.
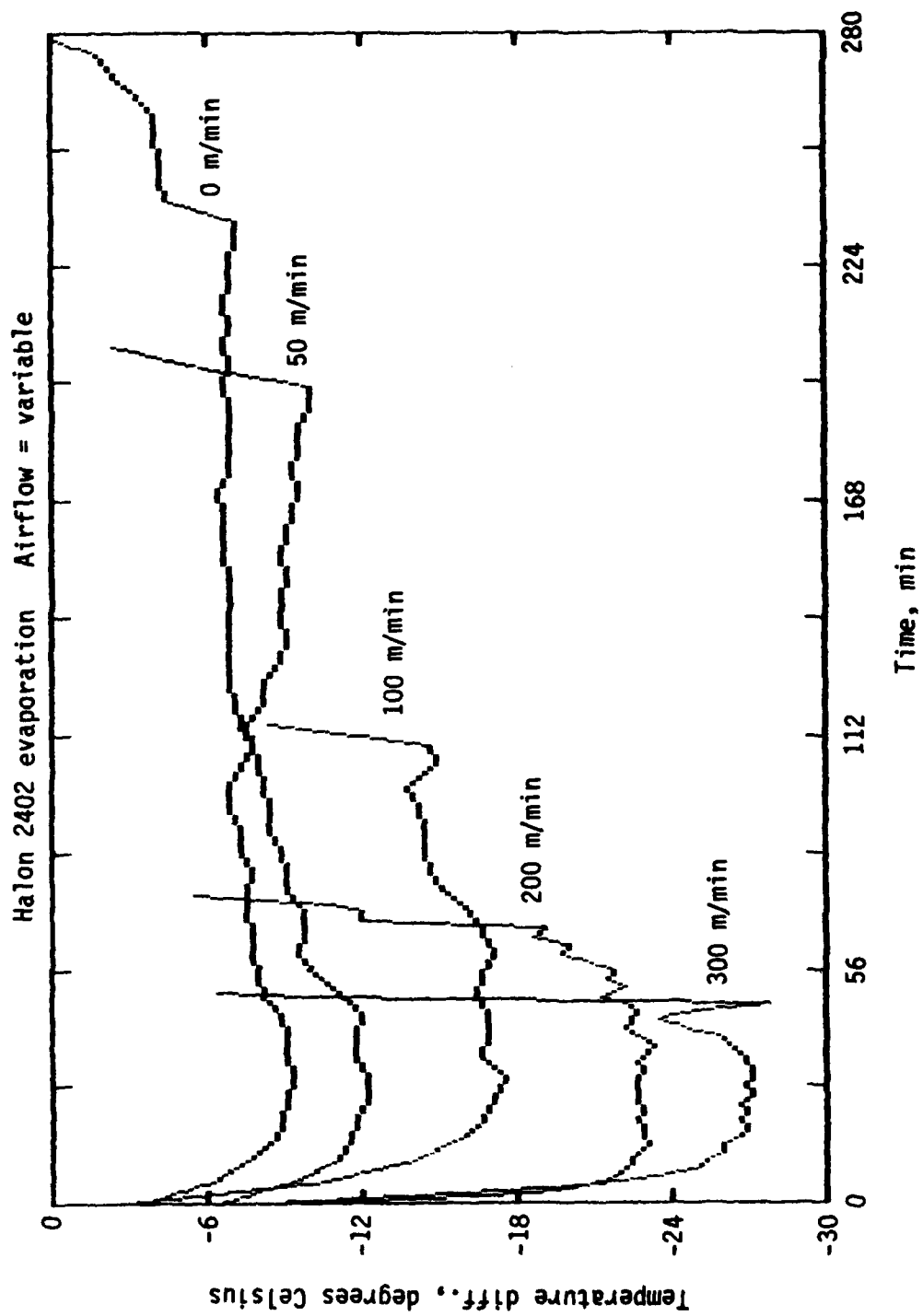
Figure 47. Temperature Difference Between Ambient Air and Halon 2402.

The difference between the Halon 2402 and air temperature at equilibrium is plotted as a function of air velocity for the five runs in Figure 48. Excluding the point for zero air velocity, the data can fit well into the second-order equation

$$\Delta T = -2.437 - 0.5091V + 2.673 \times 10^{-3}V^2 \qquad (17)$$

for T in degrees Celsius (°C) and V, the air velocity, in m/min. Equations (16) and (17) are for evaporation at an ambient temperature of near 10 °C (68 °F). Caution must be used in applying second-order equations outside the range for which they were developed.

b. Computer Modeling of Evaporation

A computer program used to model the evaporation of hydrazine propellants from ground spills (Reference 39) was modified to calculate evaporation rates for Halon 2402. The program calculates the mass transfer rate coefficient, k_m, for evaporation from the surface of a spill into the air in units of meters per hour by equating the heat transfer rate to the liquid pool to the heat required for evaporating the liquid. The heat transfer mechanisms included are: (1) convective transfer between pool and air and between pool and ground, (2) mutual radiative transfer between pool and air, and (3) solar input to the pool.

The concentration of Halon 2402 in kilograms per cubic meter in the vapor at the pool surface is calculated using the partial pressure in an ideal gas law,

$$W/V = pM/RT_{pool} \qquad (18)$$

where W is the mass of Halon 2402, V is the volume, p is the vapor pressure, and T_{pool} is the pool temperature. The total mass evaporation rate (VAPRT in the program) for a pool of area A is given by

$$VAPRT = k_m(W/V)A \qquad (19)$$
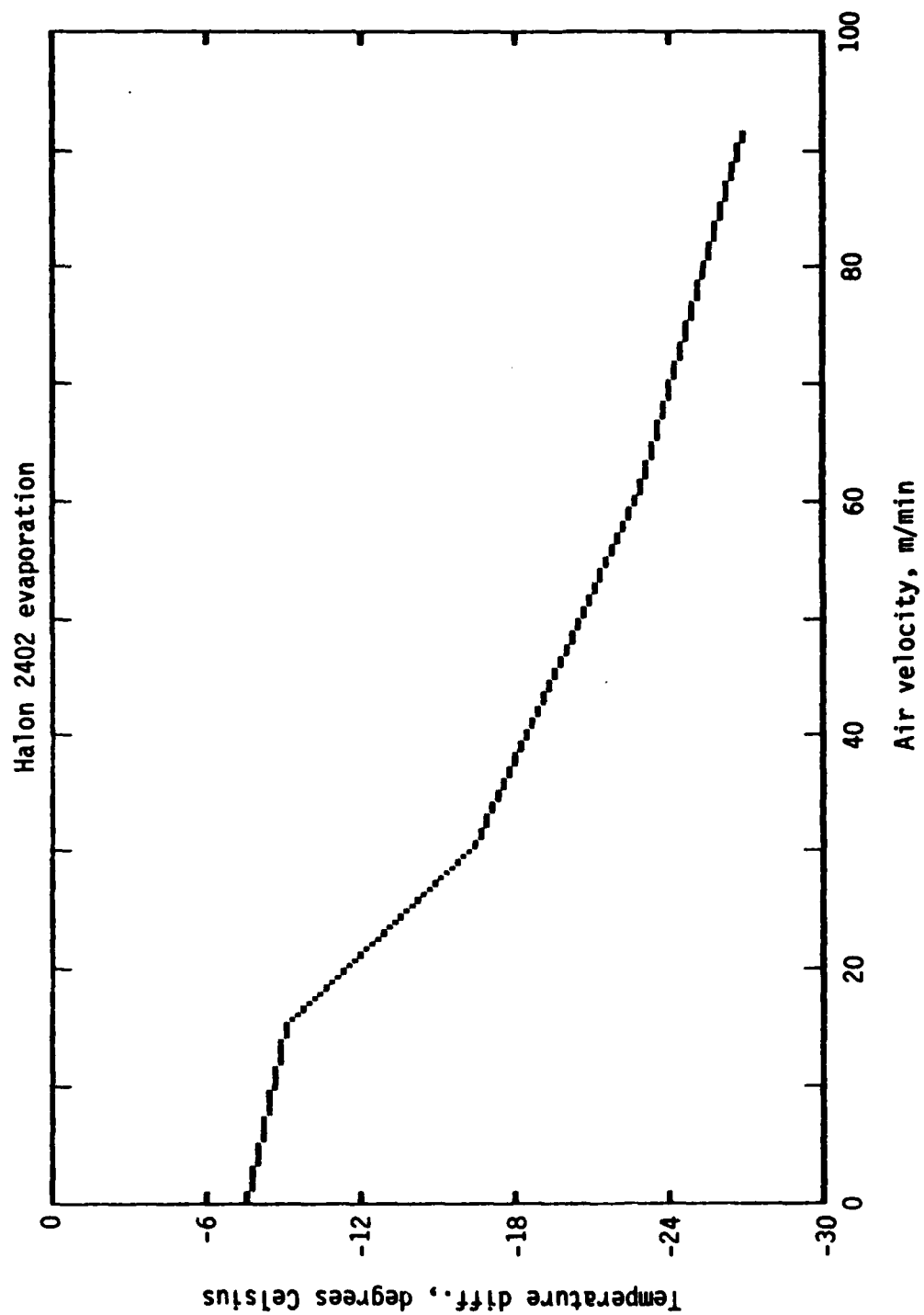
Figure 48. Temperature Difference as a Function of Time.

There are three types of program inputs: (1) constants which are assumed the same for all liquids and all environmental conditions, (2) physical and thermodynamic properties of the evaporating liquid, and (3) environmental conditions. The constants are used in the convergence routines for equilibrium pool temperature and for energy balance at equilibrium evaporation rate. Constant values are assumed for three environmental conditions: albedo (ratio of radiation reflected to radiation received) and radiative emissivities of air and the pool. The albedo, air emissivity, and pool emissivity are assigned values of 0.14, 0.75, and 0.95 (Reference 40).

Physical and thermodynamic properties as a function of temperature are calculated within the program, using polynomials in the form $A + BT + CT^2 + D/T + E/T^2 + F/T^3$, which are fit to known experimental data. In many cases, simpler forms are used (one or more of the coefficients are zero). The temperature used in the polynomials is the pool temperature for liquid properties and the film temperature for vapor film properties. As the pool temperature converges, new properties are calculated for every program loop.

The normal boiling point, vapor critical temperature, heat of vaporization at one reference temperature, and molar volume are taken from Reference 4. The collision integral for Halon 2402 - air mixtures, used in the diffusivity calculation, was determined as a function of temperature using the method given by the authors of the original program (Reference 39).

The variable inputs to the program are the diameter of the spill in meters, depth of pool in meters (pools are considered circular for simplicity), the ground roughness factor, air temperature in degrees Celsius (°C), ground temperature in degrees Celsius (°C), wind speed in meters per second (m/s), and the solar energy flux in units of Joules per square meter per hour ($J/m^2/h$). The roughness factor is a measure of the wind velocity profile above the surface of the liquid. This velocity profile is critical in controlling the eddy diffusivity. The velocity profile is assumed to follow a power law in which the wind velocity V is a function of the height Z in meters and the wind speed V_1 at Z = 1 meter,

$$V = V_1 Z^{[n/(2-n)]} \tag{20}$$

where n is the roughness factor (Reference 40). For average atmospheric condi-
tions, a value of 0.25 is reasonable for n (Reference 41) and this value will
be used for all data reported here. The minimum value for the solar radiation
is zero (at night) and it approaches 4×10^{-6} J/m^2/h on clear days during the
summer.

The modified FORTRAN computer program "SPILEVAP" is shown in
Table 35. The program calls for the name of a file containing data for the
liquid of interest. The input file for Halon 2402 is given in Table 36. The
program was run varying one factor at a time - air velocity, ambient tempera-
ture (ground and air), pool diameter, pool depth, and solar flux. The
"standard" conditions were wind velocity = 3 m/s (591 ft/min, 6.71 mi/h), air
temperature = ground temperature = 20 °C (68 °F), pool diameter = 3 meters
(area of 7.07 m^2), liquid depth = 0.0254 meter (1 inch), solar flux
= 3×10^6 J/m^2/h (shown in Table 37 as 3 MJ/m^2/h, and roughness factor = 0.25.
Three "typical" spill cases were run assuming a spill of 208 liters
(55 gallons) to give a depth of 0.0254 meter (1 inch) and a circular pool
diameter of 3.23 meters (10.6 feet). The assumed wind velocity was 3 m/s
(6.71 mi/h). The solar fluxes used were daily maximum solar fluxes of
2.5×10^6 J/m^2/h on a clear winter day at 0 °C, 3.1×10^6 J/m^2/h for a clear
spring day at 15 °C, and 3.8×10^6 J/m^2/h for a clear summer day at 30 °C
(Reference 39). One computer run was made to match an experimental condition
used in the laboratory. The air velocity = 1.524 m/s (300 ft/min), pool
diameter = 0.089 m (to give an area of 62.21 cm^2), ambient temperature
= 25.4 °C (77.8 °F), solar flux = 0.0, and pool depth = 0.008035 meter (the
pool depth in the laboratory study at half the evaporation time). The correct
roughness factor is difficult to assess; however, since all of the other cal-
culations were based on a roughness factor of 0.25, the same roughness factor
was used here. The output for these calculations is the mass evaporation rate
in kg/h (converted also to mass flux in kg/m^2/h by dividing by the area) and
the final pool temperature in degrees Celsius (°C). The results are reported
in Table 37.

TABLE 35. LISTING OF FORTRAN PROGRAM "SPILEVAP."

```
1        program spilevap
2        $debug
3        common /a/ tac,u,dspill,aspill,gn,rs,kp,tgc,dp,h,hg,ta,tpt,tp,
4        % alb,ea,ep,fm,hvapo,vaprt,ra,tg,iout
5        common /b/ iread,ident,iend,vpxx(6),denxx(6),tconxx(6),cplxx(6)
6        %,visxx(6),cppxx(6),wmol,vo,tboil,omegk,hvapl,tvap,tcp,beta,slope
7        character*64 ident
8        f(a,b,c,d,e,f,t) = a + b*t + c*t*t + d/t + e/(t*t) + f/(t*t*t)
9        iread = 0
10  10   call read
11       if ( iend .eq. 1 ) go to 36
12       fac=.2
13       zip=.001
14       ea=.75
15       tg=tgc+273.
16       rbar=(3.617+1.18*vo**.333)/2.
17       pt=101.3
18       ta=tac+273
19       tp=ta
20       tf=ta
21       do 13 i=1,100
22       tm=(tp+tg)/2.
23       vpplog = f (vpxx(1),vpxx(2),vpxx(3),vpxx(4),vpxx(5),vpxx(6),tp)
24       denl = f(denxx(1),denxx(2),denxx(2),denxx(3),denxx(4),denxx(5),
25       % denxx(6),tm)
26       tconl =f(tconxx(1),tconxx(2),tconxx(3),tconxx(4),tconxx(5),
27       % tconxx(6),tm)
28       cpl=f(cplxx(1),cplxx(2),cplxx(3),cplxx(4),cplxx(5),cplxx(6),tm)
29       visllog=f(visxx(1),visxx(2),visxx(3),visxx(4),visxx(5),visxx(6)
30       % ,tm)
31       cpp=f(cppxx(1),cppxx(2),cppxx(3),cppxx(4),cppxx(5),cppxx(6),tf)
32       vpp=10**(vpplog)
33       visl=10**visllog
34       omega=10**(slope*(alog(tf)/2.30259)+omegk)
35       visp=(27.*wmol**.5*tf**1.5/(vo**.67*(tf+1.47*tboil)))/1.E6
36       tconp=(cpp+2.48/wmol)*visp*3.6E5
```

TABLE 35. LISTING OF FORTRAN PROGRAM "SPILEVAP" (CONTINUED).

```
37        hca=.232+1.622E-5*tf+3.96E-8*tf**2

38        tcona=.06398*(tf-273.)+20.829

39        visa=1.45E-5*(tf**1.5/(tf+116))

40        dv1=.0018583*tf**1.5*(.03448+1./wmol)**.5

41        dv2=rbar**2*omega*pt/101.3

42        dv=dv1/dv2

43        y=vpp/(2.*pt)

44        visfd=wmol**.5*y+3.385*(1.-y)

45        visfn=y*visp*wmol**.5+(1.-y)*visa*5.385

46        visfm=visfn/visfd

47        denfm=(wmol*y+29.*(1.-y))*pt/(8314.4*tf)

48        cpfln=y*cpp*wmol+(1.-y)*hca*29.

49        cpfld=y*wmol+(1.-y)*29.

50        cpflm=cpfln/cpfld

51        tcofd=y*wmol**.333+3.072*(1.-y)

52        tcofn=y*tconp*wmol**.33+(1.-y)*3.072*tcona

53        tcofm=tcofn/tcofd

54        sc=visfm/(denfm*dv)

55        pr=cpflm*visfm*3.6E5/tcofm

56        hvapo=hvapl*((tcp-tp)/(tcp-tvap))**.38

57        trk1=(.0292/sc**.667)*(u*3600.)**((2.-gn)/(2.+gn))

58        trk2=dspill**(-gn/(2.+gn))

59        trk=trk1*trk2

60        fm=wmol*trk*vpp/(8.3144*tp)

61        h=1.E6*trk*denfm*cpflm*(sc/pr)**.667

62        const=(1.-alb)*rs+4.878E-5*ea*ta**4-fm*hvapo

63        tpt=tp

64        do 14 ii=1,100

65 20     gr=1.27E8*beta*dp**3*denl**2/visl**2

66        prl=cpl*visl/tconl

67        ra=gr*prl

68        if(tg-tpt)41,41,21

69 21     if(gr*prl-1700.)41,41,42

70 c      conduction region

71 41     a=1
```

TABLE 35. LISTING OF FORTRAN PROGRAM "SPILEVAP" (CONTINUED).

```
72          b=0
73          c=0
74          go to 25
75 42       if(gr*prl-3000.)43,43,44
76 c        creeping region
77 43       a=.0012
78          b=.9
79          c=.9
80          go to 25
81 44       if(gr*prl-8000.*prl**.2)45,45,46
82 c        laminar region
83 45       a=.24
84          b=.25
85          c=.25
86          go to 25
87 46       if(cr*prl-18000.*prl**.2)47,47,48
88 c        transition region
89 47       a=.3
90          b=.16
91          c=.21
92          go to 25
93 c        turbulent region
94 48       a=1.
95          b=.31
96          c=.36
97 25       hg=a*gr**b*prl**c*tconl/dp
98 18       tpt1=h*(ta-tpt)+hg*(tg-tpt)
99          tpt2=-4.878E-5*ep*tpt**4+const
100         prim=-h-hg-1.854E-4*tpt**3
101         tpnew=tpt-(tpt1+tpt2)/prim
102         crit=abs(tpnew-tpt)
103         tpt=tpnew
104         if(crit-.001)114,114,14
105 14      continue
106 114     continue
```

TABLE 35. LISTING OF FORTRAN PROGRAM "SPILEVAP" (CONTINUED).

```
107         del=tpt-tp
108         if(abs(del)-zip)113,15,15
109 15      tp=tp+fac*del
110 13      tf=(ta+tp)/2.
111 113     vaprt=fm*aspill
112         call evout
113         go to 10
114 36      continue
115         end
116         subroutine read
117         common /a/ tac,u,dspill,aspill,gn,rs,kp,tgc,dp,h,hg,ta,tpt,tp,
118       % alb,ea,ep,fm,hvapo,vaprt,ra,tg,iout
119         common /b/ iread,ident,iend,vpxx(6),denxx(6),tconxx(6),cplxx(6)
120       %,visxx(6),cppxx(6),wmol,vo,tboil,omegk,hvapl,tvap,tcp,beta,slope
121         character*64 file5, file6, ident, dummy
122         character*1 answer
123         if ( iread .eq. 1 ) go to 25
124         write(*,10)
125 10      format(' Enter name of file containing liquid properties: '\)
126         read(*,'(a)') file5
127         write(*,20)
128 20      format(' Enter name of file for output data: '\)
129         read(*,'(a)') file6
130         open (5,file=file5,status='old')
131         open (6,file=file6,status='new')
132         if ( iread .eq. 0 ) go to 60
133         ireset = 0
134         iout = 0
135 25      write(*,30)
136 30      format(' Do you wish to run another case? (y or n) '\)
137         read(*,'(a)') answer
138         if ( answer .eq. 'y' ) go to 40
139         iend = 1
140         return
141 40      write(*,50) ident
```

TABLE 35. LISTING OF FORTRAN PROGRAM "SPILEVAP" (CONTINUED).

```
142 50     format(' The current liquid is: ',a64,/,
143        % ' Will the liquid be the same for this case? (y or n) '\)
144        read(*,'(a)') answer
145        if ( answer .eq. 'y' ) go to 55
146        ireset = 0
147        close (5)
148        write(*,10)
149        read(*,'(a)') file5
150        open (5,file=file5,status='old')
151        write(*,51)
152 51     format(' Do you want a new file for the new liquid? (y or n)'\)
153        read(*,'(a)') answer
154        if (answer .eq. 'n') go to 60
155        iout = 0
156        close (6)
157        write(*,20)
158        read(*,'(a)') file6
159        open (6,file=file6,status='new')
160        go to 60
161 55     ireset = 1
162 60     iread = 1
163        write(*,1001) tac
164        read(*,*,end=70) tac
165 70     write(*,1002) u
166        read(*,*,end=80) u
167 80     write(*,1003) dspill
168        read(*,*,end=90) dspill
169 90     aspill = 3.14159 * dspill * dspill / 4.
170 100    write(*,1005) gn
171        read(*,*,end=110) gn
172 110    write(*,1006) rs
173        read(*,*,end=120) rs
174 120    write(*,1007) tgc
175        read(*,*,end=130) tgc
```

TABLE 35. LISTING OF FORTRAN PROGRAM "SPILEVAP" (CONTINUED).

```
176 130   write(*,1008) dp
177       read(*,*,end=140) dp
178 1001  format(' Input air temperature (deg C), the current value is ',
179       % f4.1)
180 1002  format(' Input wind velocity (m/sec), the current value is ',
181       % f5.2)
182 1003  format(' Input spill diameter (m), the current value is ',f5.1)
183 1005  format(' Input ground roughness factor, the current value is ',
184       % f5.2)
185 1006  format(' Input solar rate (J/m**2*hr), the current value is '
186       % ,f10.2)
187 1007  format(' Input ground temperature (deg C), the current value '
188       % 'is ',f4.1)
189 1008  format(' Input pool depth (m), the current value is ',f7.5)
190 140   if ( ireset .eq. 1 ) return
191       read(5,'(a)') ident
192       read(5,'(a)') dummy
193       read(5,*) (vpxx(i), i= 1,6)
194       read(5,'(a)') dummy
195       read(5,*) (denxx(i), i= 1,6)
196       read(5,'(a)') dummy
197       read(5,*) (tconxx(i), i= 1,6)
198       read(5,'(a)') dummy
199       read(5,*) (cplxx(i), i= 1 ,6)
200       read(5,'(a)') dummy
201       read(5,*) (visxx(i), i= 1,6)
202       read(5,'(a)') dummy
203       read(5,*) (cppxx(i), i= 1,6)
204       read(5,'(a)') dummy
205       read(5,*) wmol, vo, tboil, omegk, hvapl
206       read(5,'(a)') dummy
207       read(5,*) tvap, tcp, beta, slope
208 150   return
209       end
```

TABLE 35. LISTING OF FORTRAN PROGRAM "SPILEVAP" (CONCLUDED).

```
210 c      evout --output for "evap"
211        subroutine evout
212        common /a/ tac,u,dspill,aspill,gn,rs,kp,tgc,dp,h,hg,ta,tpt,tp,
213      1 alb,ea,ep,fm,hvapo,vaprt,ra,tg,iout
214        if (iout .ne. 0) go to 20
215        iout = 1
216        write(6,61)
217        write(6,62)
218        write(6,63)
219        write(6,38)
220 61     format(1x,'u=Wind velocity, m/sec',3x,'tac=Air temp., Deg C',3x,
221      &  'tgc=Ground temp., Deg C')
222 62     format(1x,'rs=Insolation, J/sq m.hr',3x,'gn=Gnd. roughness'
223      & ' fac.',3x,'dp=Spill depth, meters')
224 63     format(1x,'tp=Pool temp., Deg Kelvin',3x,'aspill=Spill'
225      & ' area, sq m',3x,'vaprt=Evap. rate, kg/hr',/)
226 38     format(2x,'u',6x.'tac',4x,'tgc',5x,'gn',5x,'rs',10x,'dp',6x,'tp'
227      & ,6x,'aspill',3x,'vaprt')
228 20     write(6,39) u,tac,tgc,gn,rs,dp,tp,aspill,vaprt
229 39     format(1x,f5.3,2x,f5.1,2x,f5.1,2x,f5.3,2x,e10.4,2x,f7.5,2x,
230      & f6.2,2x,f7.2,2x,f9.2)
231        return
232        end
```

149

TABLE 36. HALON 2402 INPUT FILE FOR COMPUTER PROGRAM SPILEVAP.

```
Halon 2402 (cal) 6-20-86
vpplog constants
5.75782, 0., 0., -1209.56, 0., 0.
denl constants
3690., -5., 0., 0., 0., 0.
tconl constants
40.14, 0., 0., 0., 0., 0.
cpl constants
166, 0., 0., 0., 0., 0.
visllog constants
1.45768, -4.32857e-03, 0., -92.50913, 0., 0.
cpp constants
0.11, 0., 0., 0., 0., 0.
wmol, vo, tboil, omegk, hvapl
259.83, 124.92, 322., 1.0013, 2.76e04
tvap, tcp, beta, slope
320.3, 487.5, 22.17e-04, -.39
```

TABLE 37. CALCULATED EVAPORATION RATES FOR HALON 2402.

Air flow, m/s	Ambient temp., °C	Pool diameter, m	Pool area, m^2	Pool depth, m	Solar flux, $MJ/m^2/h$	Pool temp., °C	Evaporation rate, kg/h	Mass flux, $kg/m^2/h$
Velocity varied								
2	20	3	7.068	0.0254	3	16.3	806	114
3	20	3	7.068	0.0254	3	10.8	839	121
5	20	3	7.068	0.0254	3	4.2	899	127
7	20	3	7.068	0.0254	3	-1.0	955	135
10	20	3	7.068	0.0254	3	-3.8	1033	146
15	20	3	7.068	0.0254	3	-7.9	1153	163
Ambient temperature varied								
3	-10	3	7.068	0.0254	3	6.1	666	94
3	0	3	7.068	0.0254	3	7.6	717	101
3	10	3	7.068	0.0254	3	9.1	772	109
3	20	3	7.068	0.0254	3	10.8	839	119
3	30	3	7.068	0.0254	3	12.4	909	129
3	40	3	7.068	0.0254	3	13.9	982	139
Diameter (area) varied								
3	20	1	0.785	0.0254	3	10.7	95	121
3	20	2	3.142	0.0254	3	10.0	375	120
3	20	3	7.068	0.0254	3	10.8	839	119
3	20	4	12.566	0.0254	3	11.3	1485	118

TABLE 37. CALCULATED EVAPORATION RATES FOR HALON 2402 (CONCLUDED).

Air flow, m/s	Ambient temp., °C	Pool diameter, m	Pool area, m²	Pool depth, m	Solar flux, MJ/m²/h	Pool temp., °C	Evaporation rate, kg/h	Mass flux, kg/m²/h
Pool depth varied								
3	20	3	7.068	0.001	3	12.9	934	134
3	20	3	7.068	0.01	3	11.0	849	120
3	20	3	7.068	0.05	3	10.6	834	118
3	20	3	7.068	0.2	3	10.5	828	117
3	20	3	7.068	1.0	3	10.4	824	117
3	20	3	7.068	5.0	3	10.4	823	116
Solar flux varied								
3	20	3	7.068	0.0254	0	-14.3	239	34
3	20	3	7.068	0.0254	1	-1.8	426	60
3	20	3	7.068	0.0254	2	4.9	628	89
3	20	3	7.068	0.0254	3	10.8	839	119
3	20	3	7.068	0.0254	4	15.4	1056	149
Typical cases								
3	30	3.23	8.194	0.0254	3.8	16.1	1258	178
3	15	3.23	8.194	0.0254	3.1	10.6	957	135
3	0	3.23	8.194	0.0254	2.5	4.6	710	100
Comparison to laboratory data								
1.524	25.44	0.089	0.00622	0.0254	0.0	-7.9	0.25	40

3.   Discussion

The result obtained in the laboratory comparison calculation is remarkably close to the experimental value, 40 kg/m^{2}h = 0.067 g/cm^2/min compared with the experimental value of 0.0646 g/cm^2/min for an air velocity of 91.4 m/min (300 ft/min). The temperature comparison, however, is not as close as desirable. The experimental pool temperature is -1.4 °C (29.5 °F) and the calculated temperature is -7.9 °C (17.8 °F). Moreover, the evaporation rate is highly dependent on the roughness factor; the factor of 0.25 used for the laboratory experiment is, at best, a guess. Nevertheless, the excellent agreement between the experimental and calculated rates gives some assurance that the calculated rates are approximately correct.

The calculations show that the mass flux (the evaporation rate per unit area) is almost independent of pool size. There is a small increase in the mass flux as the pool size decreases (Table 37); however, the change is negligible. Thus the calculated mass fluxes can be multiplied by the pool area to determine approximate evaporation rates. On the other hand, the evaporation rate is highly dependent on the pool depth below approximately 0.01 meter (0.39 inch). For very shallow pools, the evaporation rate increases rapidly with decreasing depth (Figure 49).

As determined in the laboratory experiment, the evaporation rate for Halon 2402 is an approximately linear function of the air velocity (Figure 50). The intercept is, however, quite different from that found earlier in Equation (16), where the evaporation rate at very low air velocities approached zero. This seeming lack of agreement is due primarily to the solar flux difference (zero solar flux for the laboratory). The data plotted in Figure 50 exhibit some curvature at low velocities. Unfortunately, the computer program SPILEVAP tends to give erratic results at very low air velocities and large spill areas so that it is difficult to check the results against the functional dependence on air velocity determined in the laboratory. The data shown in Figure 50 are fit very well by the linear function

$$Flux = 108.6 + 3.678 \tag{21}$$

Here, the flux has units of kg/m^2/h and V has units of m/s.

153
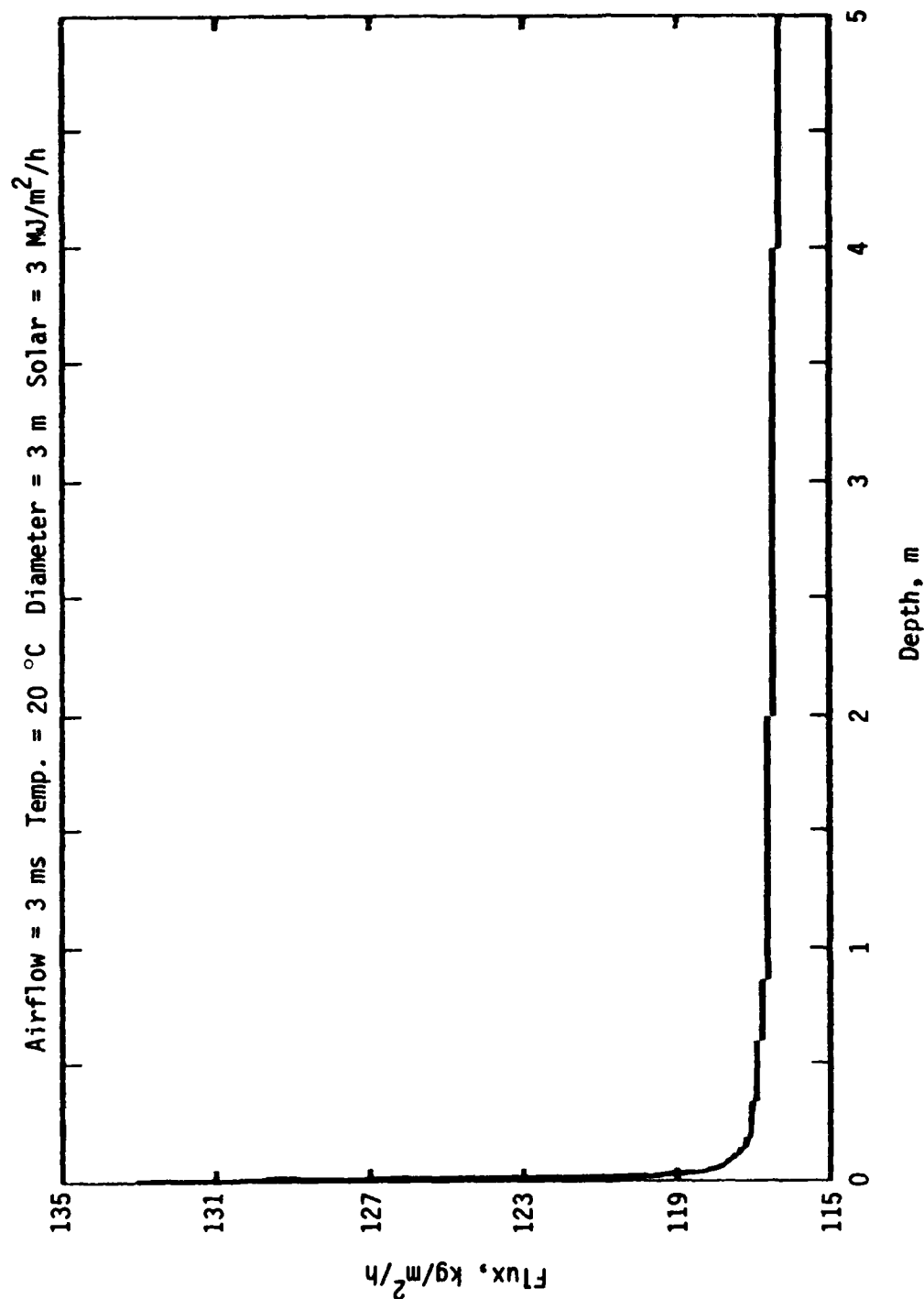
Figure 49. Calculated Evaporation Flux as a Function of Pool Depth for Air Velocity of 3 m/s, Ambient Temperature of 20 °C, Pool Diameter of 3 meters, and Solar Flux of 3 MJ/m²hr.
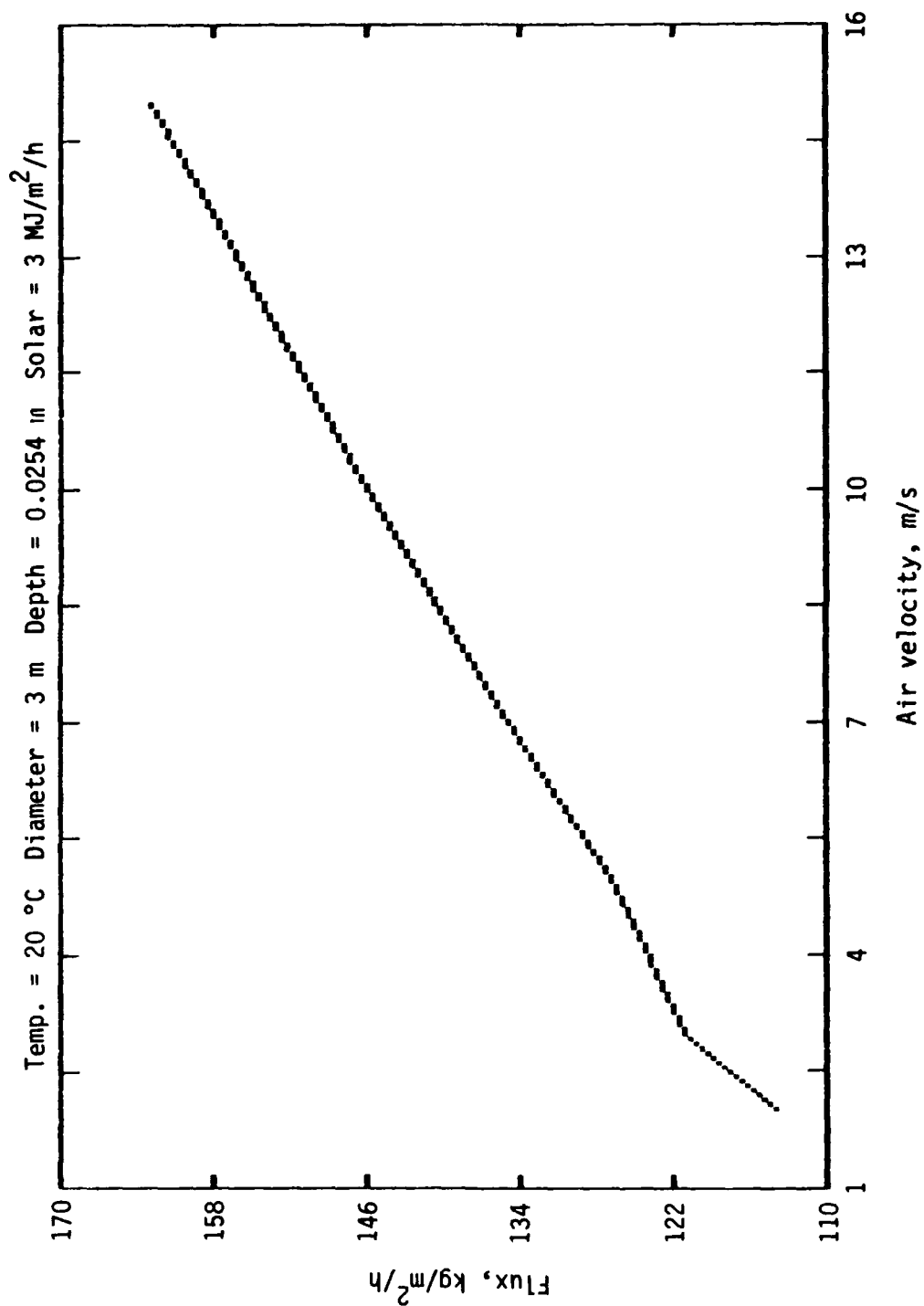
Figure 50. Calculated Evaporation Flux as a Function of Air Velocity for Ambient Temperature of 20 °C, Pool Diameter of 3 meters, Pool Depth of 0.0254 meter, and Solar Flux of 3 MJ/m2hr.

The temperature drop of the liquid Halon 2402 as a function of air velocity is shown in Figure 51. As expected, and as seen earlier (Figure 48), the temperature decreases as the air velocity increases. The data in Figure 51 can be fit with a polynomial of the form,

$$T = -3.69 + 4.57V - 0.167V^2 \tag{22}$$

where the temperature drop is in degrees Celsius (°C) and V has units of m/s. Note that the temperature drop, according to Equation (22), will have a negative value at a zero air velocity. At zero air velocity, the temperature of the pool will be higher than that of its surroundings. This is a result of the warming effect of the solar radiation, which has a flux of $3 \times 10^6 J/m^2/h$ in this series of calculations.

The dependence of the mass flux on air and ground temperature (assumed equal for simplicity) is not as strong as might have been expected (Figure 52). Moreover, the final pool temperature is not highly dependent on the ambient temperature (Table 37), being much more dependent on the solar flux (see below). The functional dependence of the flux with ambient temperature is highly linear. The data in Figure 52 are fit very well with the linear function

$$Flux = 101.5 + 0.9114T \tag{23}$$

with the mass flux in $kg/m^2/h$ and the temperature in degrees Celsius (°C). The data indicate that in the temperature ranges normally encountered, the evaporation flux increases about 0.8 percent per degree Celsius.

The Halon 2402 evaporative flux depends strongly on the solar flux (Figure 53). The function is almost perfectly linear and the data can be fit with the equation

$$Flux = 32.4 + 28.9S \tag{24}$$

with the mass flux in $kg/m^2/h$ and S the solar flux in $MJ/m^2/h$. Note that the dependence of evaporation rate on solar flux is much stronger than the dependence on temperature. This indicates that hazards of Halon 2402 spills are
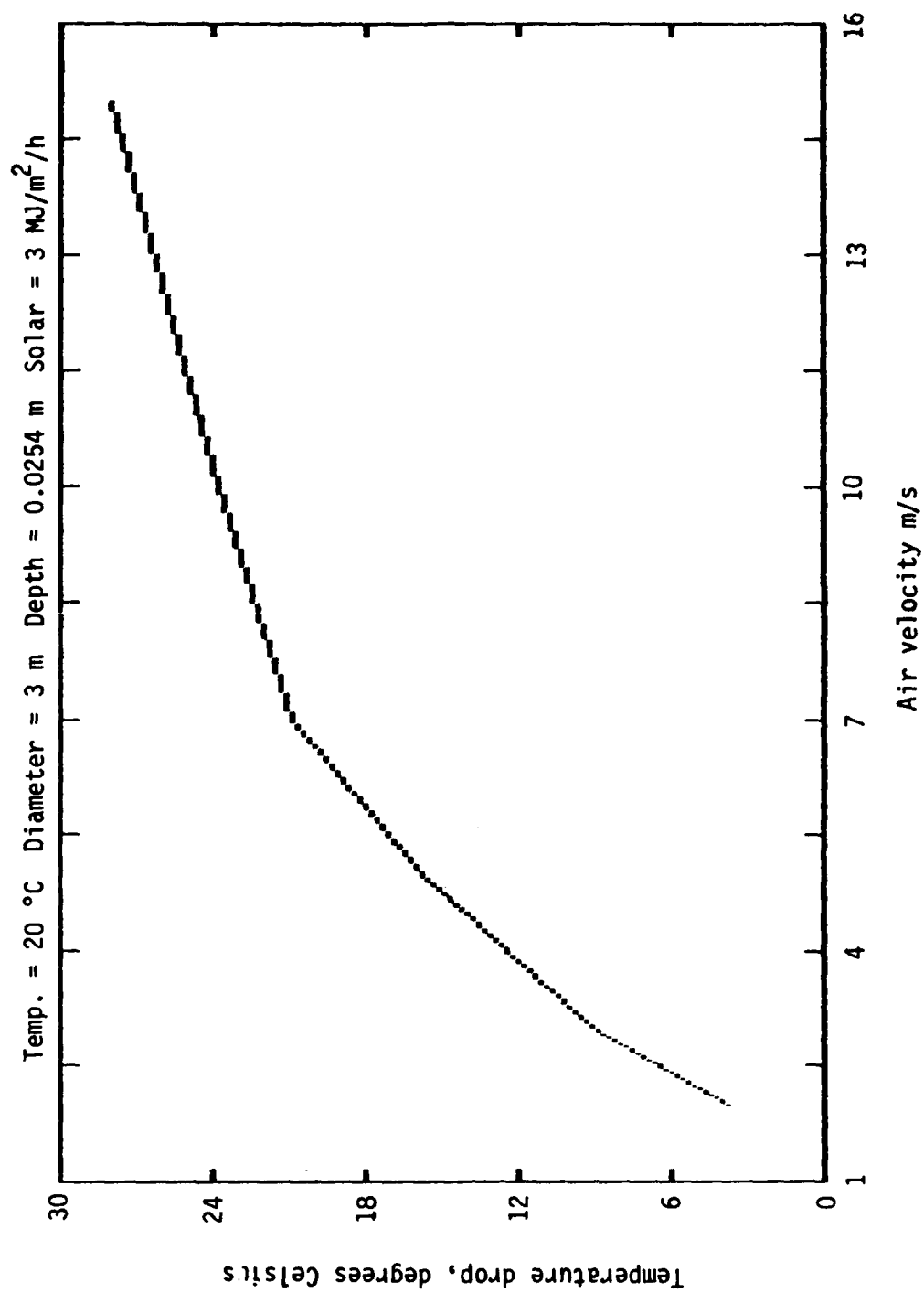
Figure 51. Calculated Temperature Drop as a Function of Air Velocity.
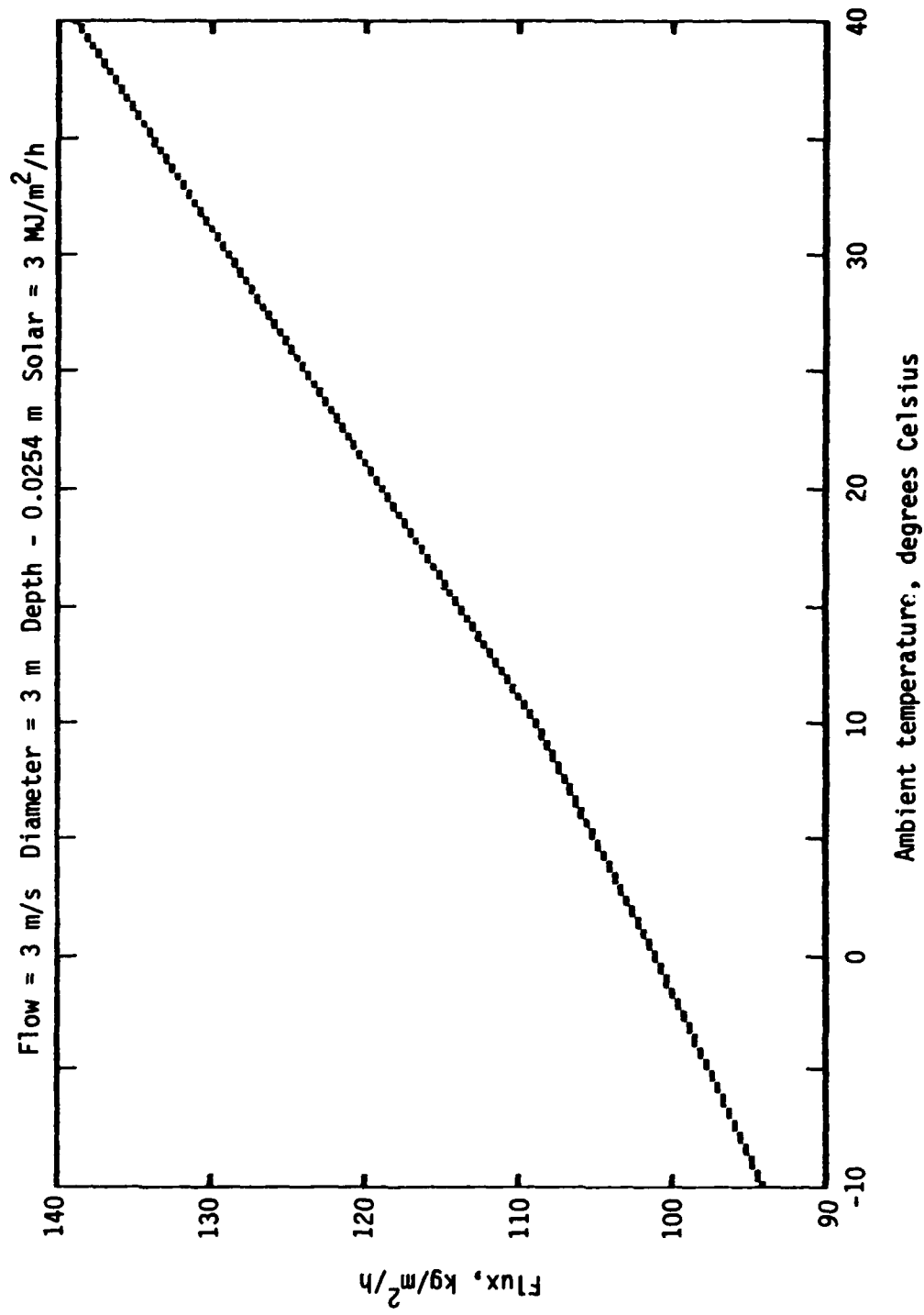
Figure 52. Calculated Halon 2402 Evaporation Flux as a Function of Ambient Temperature for Air Flow of 3 m/s, Pool Diameter of 3 meters, Pool Depth of 0.0254 meter, and Solar Flux of 3 MJ/m2hr.
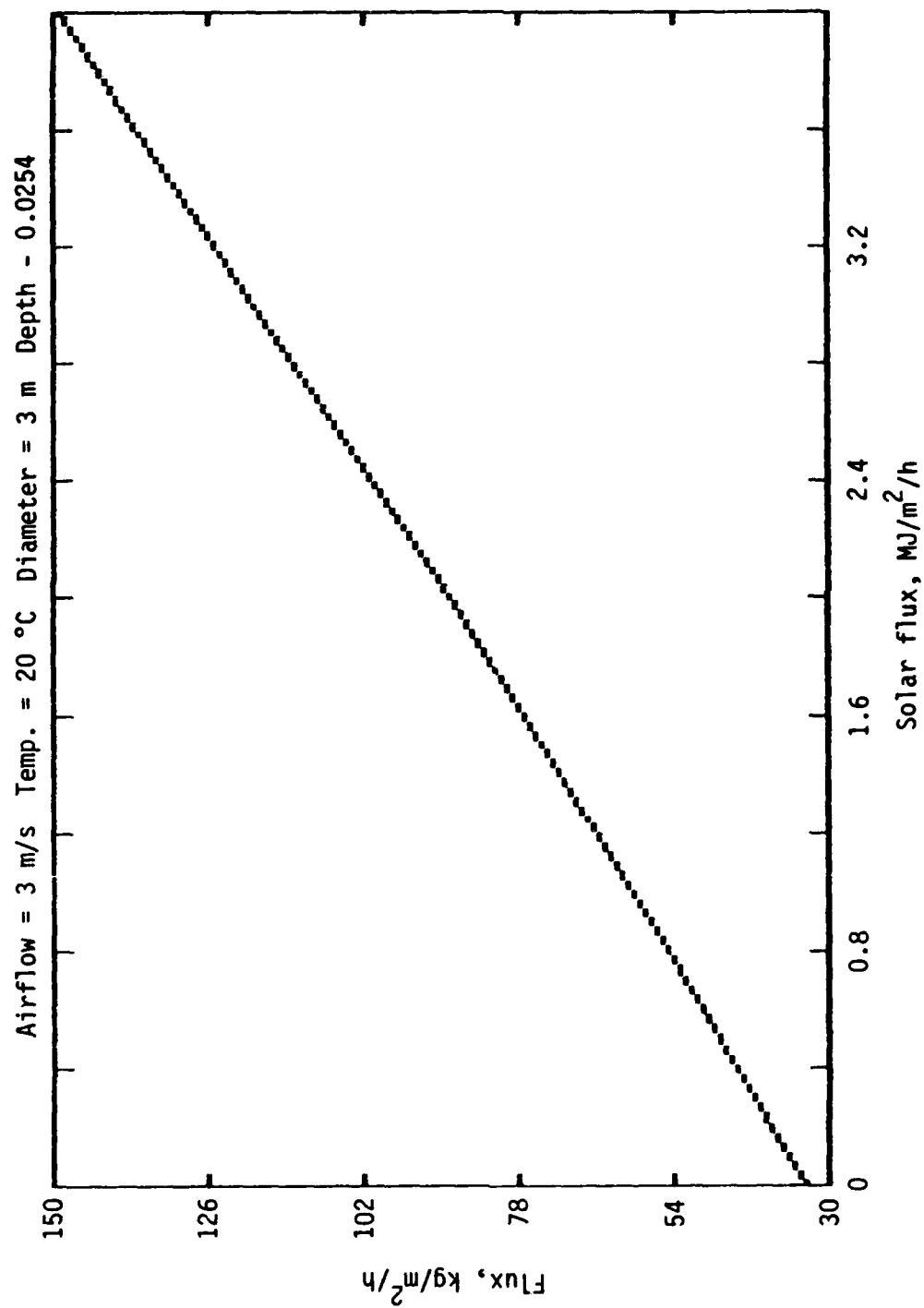
Figure 53. Mass Flux as a Function of Solar Flux for Halon 2402 Evaporation at Air Flow of 3 m/s, Ambient Temperature of 20 °C, Pool Diameter of 3 meters, and Pool Depth of 0.0254 meter.

much more dependent on the solar radiation (night, day, cloudy, clear) than on the temperature. Equation (24) indicates that the evaporation rate for zero solar radiation is 32.4 kg/m^2/h. This value, determined for an air velocity of 3 m/s, is very close to those found in the laboratory study (Table 37). For the highest velocity tested, 300 ft/min or 1.524 m/s, the experimental value is 38.6 kg/m^2/h.

The temperature drop owing to evaporation is also a strong function of the solar flux (Figure 54). At larger values of the solar flux, the pool temperature approaches, and may exceed, the ambient air temperature. The data for the case with an air flow of 3 m/s (9.8 ft/s), an ambient temperature of 20 °C (68 °F), and a pool diameter and depth of 3 meters (9.8 feet) and 0.0254 meter (1 inch), respectively (Figure 54), can be fit with a second degree polynomial

$$T = 33.77 - 11.94S + 1.19S^2 \qquad (25)$$

for T in degrees Celsius (°C) and S in MJ/m^2/h. Note that these data predict a temperature drop of 34 °C (93 °F) for a zero solar flux. This is in poor agreement with the value of 20.6 °C (69 °F) calculated by extrapolation of data in Table 34 (Figure 48) to a flow rate of 590.6 ft/min (equivalent to 3 m/s). On the other hand, the shape of the experimental curve (Figure 48) indicates that extrapolation gives an estimate which is too high and that, therefore, the agreement is better than indicated by these numbers. Unfortunately, Equation (17) cannot be used to determine the temperature drop directly since this equation is second-order and cannot be applied outside the range of data to which it was fit.

The calculations for typical, clear winter, spring, and summer days show repspective evaporation rates of 710, 957, and 1258 kg/h for a 208-liter (55-gallon) spill to give a depth of 2.54 cm (1 inch) if there is a 3 m/s (6.7 mph) wind. The respective times required for complete evaporation would be approximately 38, 28, and 21 minutes. At night, the evaporation rates would be considerably lower.
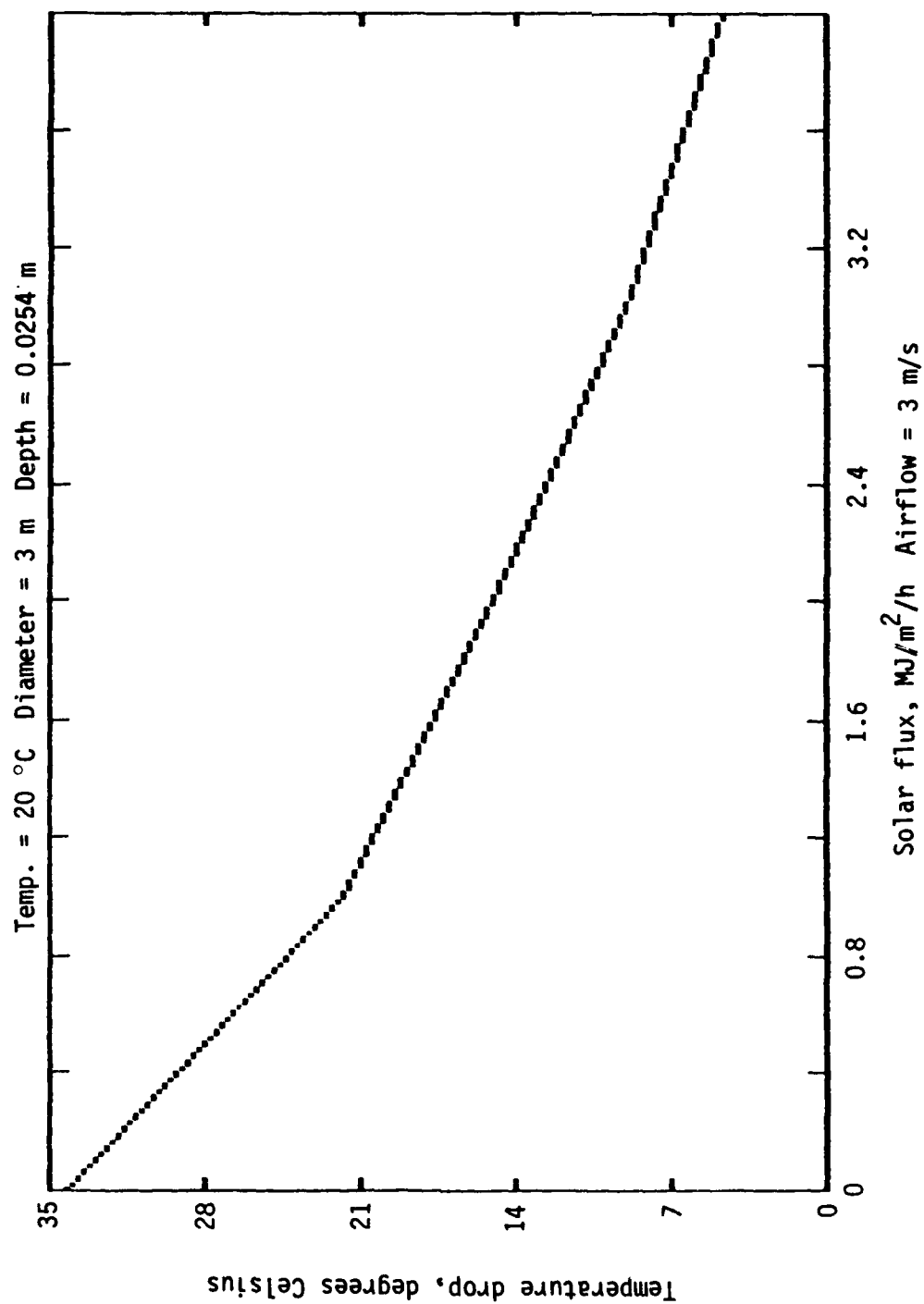
Figure 54. Temperature Drop as a Function of Solar Flux for Halon 2402 With Air Flow of 3 m/s, Ambient Temperature of 20 °C, Pool Diameter of 3 meters, and Pool Depth of 0.0254 meter.

4. Conclusions

   a. A computer program is available to predict evaporation rates under a variety of conditions for Halon 2402 spills. If desired, the program can be used to generate tables for quick reference to determine the evaporation rate for a given spill. The interactive program has been written to read in files of physical parameters and can, therefore, be quickly adopted to other materials.

   b. The evaporation rate is approximately proportional to the spill pool area and approximately independent of the pool depth for pools deeper than 1 cm. For shallower pools, the rate increases dramatically as the depth decreases.

   c. The most important determining factors for evaporation fluxes (rates per unit area) are the wind velocity and the solar flux. Ambient temperature is somewhat less important, except at night.

   d. Evaporation rate is a linear function of ambient temperature and solar flux. Example equations are derived in this unit for a 3 m/s (6.7 mph) wind. The computer program and fitting techniques can be used to develop equations for other conditions.

   e. The dependence of mass flux on air velocity is nonlinear and can be predicted with a second order equation. The flux begins to level off at high wind velocities.

   f. As a rough rule-of-thumb, a daytime spill of 208 liters (55 gallons) of Halon 2402 to give a pool depth of 2.54 cm (1 inch) will require about 1/2 hour to evaporate in a moderate 3 m/s (6.7 mph) wind. Extreme variations in wind and solar flux (day to night) will change this time. In addition, the evaporation rate (but not the flux) will be highly dependent on the pool area (which, in this case, is controlled by the depth).

   g. Under a variety of conditions, a rule-of-thumb estimate for an evaporation flux for a Halon 2402 spill during the day, is 100 to 120 kg/m^2/h (1.1 to 1.4 gal/ft^2/h). At night, the rule-of-thumb estimate drops to about 30 kg/m^2/h (0.4 gal/ft^2/h) and becomes very temperature dependent.

162

C. PERSONNEL EXPOSURE

Halon concentrations were determined during Halon transfer and application operations. The data obtained are discussed in terms of concentrations experienced by personnel during operations performed with Halon 2402.

1. Experimental

a. Transfer Operation

Grab samples were collected in 1-liter glass containers while pumping Fluobrene (Montedison Halon 2402) from a (208-liter) 55-gallon drum to another container with a Fluid-Metering Incorporated (FMI) Model RP D electrically operated laboratory pump. The pumping operation was performed in a 55-meter (18-foot) square, 4-meter (13-foot) high, corregated steel building. The building was ventilated by a wind-operated exhaust fan in the ceiling and by an approximately 15 cm (6-inch) space between the roof and the wall around the structure. Three samples were collected. Samples 1 and 3 were taken from ambient air in the center of the building, respectively, before and after the pumping operation. Sample 2 was collected during the pumping operation in the vicinity of the operating personnel.

The grab samples were analyzed on the HP 5880 GC, using the following parameters: column flow rate, 1 mL/min helium; flow with makeup gas, 30 mL/min helium; hydrogen flow, 30 mL/min; air flow, 450 mL/min; split ratio, 50:1; reference liquid Halon 2402 sample size, 0.05 µL; gas sample size, 250 µL; injection port temperature, 200 °C; oven temperature, isothermal at 35 °C; FID detector temperature, 250 °C. For three reference runs, the average chromatograph peak area for injection of 0.5 µL (109.2 µg assuming a density of 2.163 g/µL at 25 °C, Reference 4) was 750,373 AU with an average deviation of 81,791 AU. This corresponds to a sensitivity of 6872 AU/µg. The area of the peak obtained in the sample analysis is divided by this sensitivity factor to determine the number of micrograms of Halon 2204 in the 250-µL sample. This mass is converted to moles using the molecular weight of 259.84 for Halon 2402. At the laboratory temperature of 30 °C and pressure of 630 Torr, the volume occupied by one mole of a gas is 36.705 liters. This permits a calculation of the volume of Halon 2402 in the 250-µL sample and, therefore, a calculation of the concentration in parts per million by volume. The data given in Table 38 are for five determinations on each sample.

163

TABLE 38. HALON CONCENTRATIONS DURING SAMPLING.[a]

Sample number	Peak area, AU	Halon 2402 mass, µg	Halon 2402, µmole	Concentration, ppm
1	b	b	b	<1
2	1845 ± 162	0.2684	1.033×10^{-3}	152 ± 30
3	722 ± 14	0.0962	3.702×10^{-4}	54 ± 7

[a]Numbers following data are average deviations or estimated errors.
[b]Not detected.

Halon 2402 has a gas chromatography retention time of 1.51 minutes when chromatographed under the conditions used in this experiment. No peak at this value was detected in Sample 1, though a very small peak at 1.43 minutes retention time was observed. This same peak was also observed as an additional peak in the chromatograms of Samples 2 and 3 and apparently is due to an air contaminant other than Halon 2402 in the storage building used for the transfer. Other agents, including Halon 1211 and AFFF, are kept in this building.

b.   Operator Exposure Tests

Operator exposure tests were run under a worst-case condition. Halon 2402 was dispensed with the operator standing in a test facility constructed of 0.365 cm (1/4-inch) aluminum sheet. The inside dimensions were 2.3 meters (7.4 feet) high, 1.0 meter (3.4 feet) wide, and 3.7 meters (12 feet) long. Six solenoid-activated grab-sample bottles were fixed within the structure. Bottles 1-5 were suspended off the floor with rebar. Bottle 6 was mounted on a concrete block. The locations are shown in Figure 55.
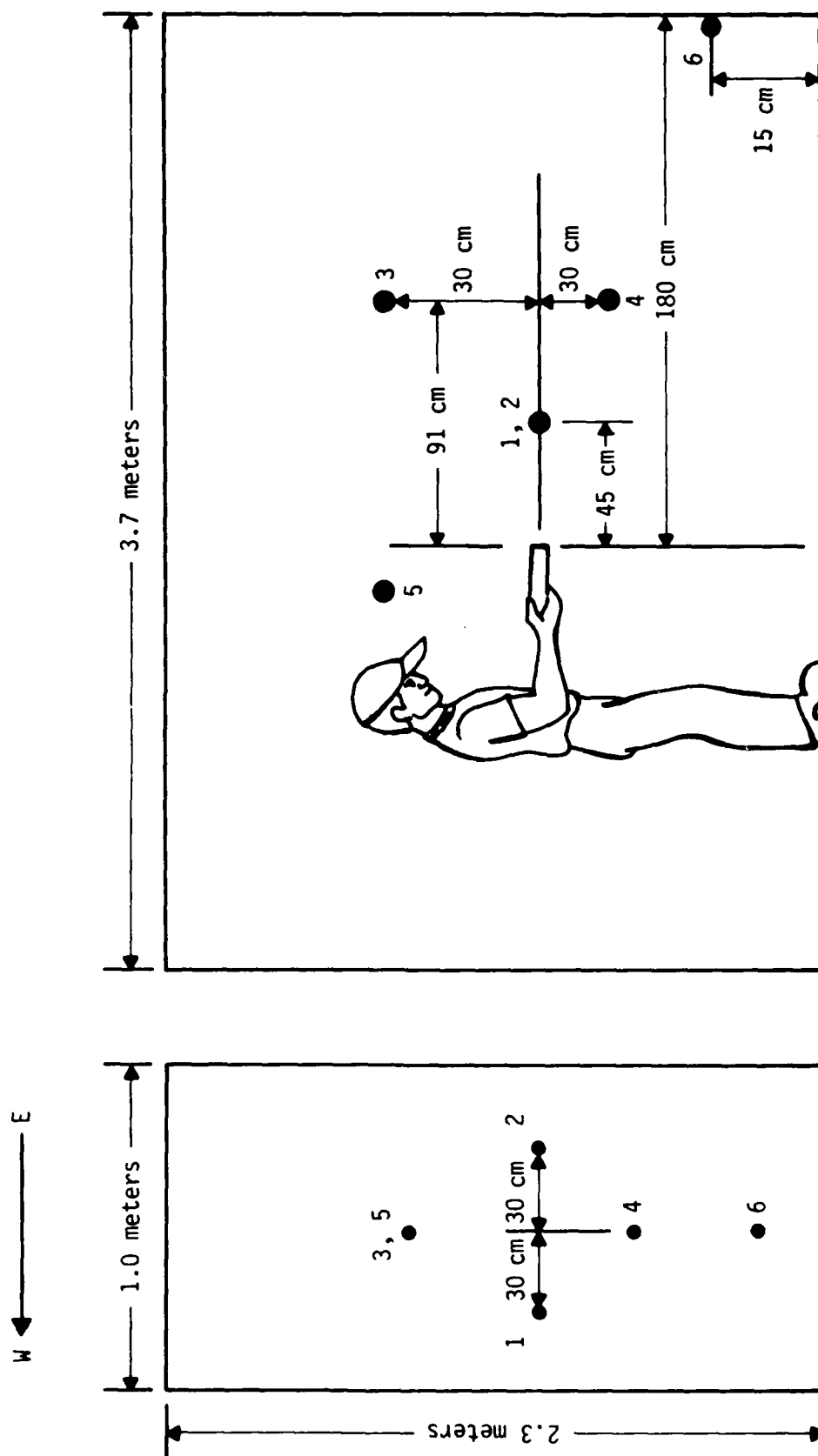
Figure 55. Operator Exposure Test Cell Dimensions and Sample Bottle Locations.

Halon 2402 was dispensed from a 1.27 cm (1/2-inch) converging brass nozzle at 4.1 kg/s (9 lb/s) toward the open end of the building with the operator standing 1.8 meters (6 feet) from the opening. The solenoid valves were activated approximately 7 seconds from the start of the flow. A crosswind caused recirculation within the test area.

The samples collected were analyzed by gas chromatography. A 2000 ppm standard was prepared in a gas cylinder by the Air Force Weapons Laboratory (AFWL). The cylinder was pressurized to give a dilution factor of 1.8084; however, the dilution factor for the sample cylinders was the same; therefore, there was no need to take the factor into account. Three 100 µL injections yielded an average peak area of 11.42 ± 0.08 AU, giving a calibration factor of 175.1 ± 1.2 ppm/AU. Either three or four injections were taken from each sample container and the peak areas were determined and averaged. From these, the concentrations were determined. The data are presented in Table 39.

c. Fire Scenario Exposure

During the large-scale pit fire tests discussed earlier in Section II, grab samples were collected in the firefighter's breathing area. One sample was collected for each of the three tests (one test with Halon 1211 and two tests with Halon 2402). The samples were analyzed by gas chromatography on the HP 5890A GC.

The GC parameters for the Halon 1211 analysis were: column pressure, 120 kPa; column flow rate (He), 0.77 mL/min; total (column plus makeup gas) flow rate, 39 mL/min; split vent flow rate, 153 mL/min; split ratio, 199.7; oven temperature, 35 °C isothermal; injection port temperature, 100 °C; detector temperature, 150 °C; detector, electron capture. The 1211 standard was prepared from an aliquot from the head space over liquified Halon 1211. The Halon 2402 standard was prepared by injecting 1.0 µL of liquid agent into a 250 mL glass gas sampling bulb to prepare a 971 ppm standard. The sample containers were pressurized to 4 lb/in.^{2}g with nitrogen gas before sample removal. The results are given in Table 40.

TABLE 39. HALON CONCENTRATIONS IN OPERATOR EXPOSURE TESTS.[a]

Sample	Gas chromatograph peak area, AU	Concentration, ppm	Location with respect to nozzle
Standard	11.36		Standard
	11.36		
	11.55		
	11.42 ± 0.11	2000	
1	3.77		0.45 m (1.5 ft) in
	3.52		front, 0.3 m (1 ft) to
	3.59		right, same height
	3.63 ± 0.10	635 ± 22	
2	4.05		0.45 m (1.5 ft) in
	3.86		front, 0.3 m (1 ft) to
	4.18		left, same height
	4.03 ± 0.12	706 ± 26	
3	2.68		In line, 0.91 m (3 ft)
	2.73		in front, 0.30 m (1 ft)
	2.67		above
	2.69 ± 0.02	471 ± 7	
4	34.72		In line, 0.91 m (3 ft)
	34.76		in front, 0.30 m (1 ft)
	35.03		below
	34.84 ± 0.13	6102 ± 65	
5	3.30		Operator breathing area
	3.00		
	3.30		
	3.20 ± 0.13	560 ± 24	
6	50.15		In line, 1.8 m (6 ft) in
	50.79		front, 15 cm (6 in) off
	50.35		ground
	50.75		
	50.51 ± 0.26	8846 ± 107	

[a]The uncertainties are the average deviations.

167

TABLE 40. FIREFIGHTER EXPOSURE LEVELS, LARGE-SCALE PIT FIRE TESTS.

Test	Number of determinations	Concentration,[a] ppm
1 (1211)	3	32.4 ± 1.0
2 (2402)	6	188 ± 12
3 (2402)	6	164 ± 28

[a]With standard deviation.

2. Discussion

The highest concentration determined in the transfer operation was 152 ppm. The recommended maximum exposure time is 10 minutes for concentrations of Halon 2402 up to 500 ppm (Reference 34). Unfortunately, this recommendation gives no lower limit for the concentration. Although the concentration determined was considerably lower than 500 ppm, the exposure time can be prolonged owing to the time required for pumping operations (in the present case it was nearly 1 hour). Moreover, the building used for the test transfer was well ventilated and only small amounts of liquid were transferred. It is expected that for transfer of large amounts of liquid Halon 2402 within a building with less airflow, an exposure to a concentration above 500 ppm for a period longer than 10 minutes is not only possible, but likely.

As an example, consider the following. If a 1 ft^2 surface area of Halon 2402 is exposed to the air within a building, the predicted evaporation rate (Table 34) for zero airflow and zero solar flux is given by the product of the flux, 7.5 kg/m^2/h, and the area, 0.0929 m^2. In one hour, the amount of material evaporated would be 0.697 kg or 2.68 moles. This amount of material will occupy a volume of 0.0656 m^3 at 1 atmosphere pressure and 25 °C. If the evaporation occurred in a sealed room, 3 meters (10 feet) on a side (volume = 28.32 m^3), the concentration at the end of one hour would be 2300 ppm, well above the U.S. Military guidelines. Even if the room volume were increased by a factor of four, the exposure would be greater than 500 ppm.

The sample concentrations determined in the operator exposure tests ranged from 471 ppm (0.05 percent by volume) to 8846 ppm (0.88 percent). The concentration in the operator breathing area was 6102 ppm (0.06 percent). This test was carried out under a worst-case scenario; nevertheless, it shows that it is possible for Halon 2402 concentrations encountered by firefighters to greatly exceed recommended levels and, in the present test, to approach levels considered immediately dangerous.

Lower levels were found in the fire scenario tests; however, even here the levels were well above 100 ppm. Since the firefighters fought the fire from upwind, the levels found are the minimum which would be expected. With adverse winds, the levels could be much higher.

3. Conclusions

a. Agent transfer and filling operations involving halon 2402 in indoor locations are likely to lead to high and possibly dangerous concentrations. Such operations should proceed outside or in large, well-ventilated areas.

b. Under some fire scenarios (adverse winds, topographic obstructions), firefighters will encounter unacceptably high levels of Halon 2402.

c. *The use of respiratory devices is advisable for both personnel handling Halon 2402 and firefighters.*

D. DECOMPOSITION

1. Objectives

A review of the possible decomposition products for Halon 2402 when used in a fire is reported. Both experimental and previous research data are used to assess the dangers of Halon 2402 decomposition.

2. Experimental

a. Concentrations in Enclosed Fires

During extinguishment of enclosed fires in the "smokehouse," a concrete block building used for fire training at Kirtland AFB, grab samples were collected. The sample collection employed six solenoid-activated, evacuated stainless steel containers for each of two tests using Halon 2402 to extinguish fires of JP-4. The tests are identified as Test 2 and Test 3, Test 1 being an earlier test during which samples were not collected. In Test 2, the fire pan was placed in the center of the room. In Test 3, the fire pan was placed near the northeast corner of the room.

Gas chromatographic (GC) analyses were performed on the HP 5880A GC with FID and Column 1. The temperature was programmed to hold 30 °C for 3 minutes, to ramp at 20 °C/min to 200 °C, and to hold at 200 °C for 4 minutes. The initial chart speed was 4 cm/min and was reduced to 1 cm/min at 3 minutes elapsed time. The injections were performed with a 50:1 split and a column flow of 1.2 mL/min of Helium.

Nitrogen was added to all sample containers to bring them to 207-750 Torr (4.0-5.5 lb/in.^{2}) over initial container pressures. Samples of 200 μL each were removed from the cylinders and were injected into the gas chromatograph. The volume reproducibility was better than 2 percent. The gas chromatograms exhibited large numbers of peaks. Comparison of these with chromatograms obtained from JP-4 fumes and burning JP-4 showed no new peaks in the Halon-extinguished fire samples other than a large peak with a retention time of 0.73 to 0.75 minutes. This peak was assigned to Halon 2402 based on chromatographs of pure halon.

Spectra of JP-4 vapor (Figure E-1, Appendix E, Volume II) and of the emissions from JP-4 fires (Figure E-2) were obtained for comparison with those from Halon 2402 extinguished fires. The retention times and peak areas, as percentages of the total area, are shown in Tables E-1 and E-2. The chromatograph of Sample 2, Test 1, a typical sample, is also shown (Figure E-3) and the data are presented in Table E-3. Only one new peak, with a retention time of approximately 0.75 minute, was observed for the fires extinguished with Halon 2402. No other materials from the Halon 2402 were found.

Integrated areas of the Halon 2402 peaks were determined from the integrator; and the calibration procedures reported in Appendix F (Volume II) were used to determine the concentrations, which were adjusted to reflect the actual final container pressures. The results are shown below in Table 41.

b.   Raman Studies of Decomposition Products

Raman spectroscopy, which determines the light scattered from a chemical species, can be used as a passive probe for the study of active systems. Various types of analytical determinations can be made without perturbing the system under study. Halons and their pyrolyzed products, having highly polarization-sensitive vibrations, should be readily analyzed. Halon 2402 has been pyrolyzed, and the products have been identified by GC/MS and Raman spectroscopy (Reference 42).

A tube furnace with a specially designed quartz tube, having detachable nitrogen traps on each end and capable of holding a vacuum, was used. To simulate the combustion process, Halon 2402 was frozen in one of the nitrogen traps, and the whole system was brought to high vacuum. The Halon 2402 was then allowed to vacuum transfer through the pyrolysis tube, which was at approximately 790 °C, to the other nitrogen trap. The products were vacuum-distilled, and the fractions captured in sealable cuvettes.

A second experiment was conducted using nitrogen gas to transfer the Halon 2402 through the pyrolysis tube. The system, not connected to the vacuum line, was purged with nitrogen at room temperature, and the halon was introduced to the nitrogen inlet. The nitrogen gas carried the halon through the pyrolysis tube, and the pyrolysis products were captured in a series of three nitrogen traps on the opposite side. The products were vacuum-transferred to the vacuum line, and distillations were performed as above. A third experiment used oxygen as the carrier gas.

The Raman spectral data were collected on an instrument composed of:

(1)   An EG&G Princeton Applied Research Model 1420 intensified silicon photodiode array tube coupled with its model 1218 solid-state detector controller, and the Model 1215 computer console.

171

TABLE 41. HALON 2402 CONCENTRATIONS IN GRAB SAMPLES.

Sample	Sampling time,[b] s	Grab sample coordinates[a]			Approximate position	Concentration, ppm
		x, cm	y, cm	z, cm		
Test 2						
1	10	42	124	16	N wall floor	4997
2	60	42	124	16	N wall floor	6460
3	10	150	183	168	Center	--[c]
4	60	150	183	168	Center	448
5	10	268	60	168	SE corner	219
6	60	268	60	168	SE corner	416
Test 3						
7	10	29	180	168	North wall	1508
8	60	29	180	168	North wall	1564
9	10	150	183	15	Center floor	4839
10	60	150	183	15	Center floor	6206
11	10	150	183	168	Center	1346
12	60	150	183	168	Center	2164

[a]Location of the grab sample containers with respect to a coordinate system with the northeast corner of the room as the origin, the north wall as the y axis, and the east wall as the x axis.

[b]Elapsed time following complete extinguishment.

[c]Halon 2402 not detected.

172

(2) A SPEX Model 1877 Triplemate monochrometer.

(3) A Coherent Model CR-4 Argon Ion Laser, capable of producing over 3 watts of continuous power at the 488.0 nm line.

Spectra in the range of 100 cm^{-1} to 1000 cm^{-1} (cm^{-1} = wavenumber) can be obtained at a single setting of the monochrometer. Since Raman spectra of many of the thermal degradation products are not available, the Finnigan Series 4900 GC/MS was used to help identify products.

Each Raman spectrum required 6 minutes for collection: three minutes for the signal spectrum and three for the background. A Raman spectrum normally requires the subtraction of the background spectrum, taken with the excitation source off, from the signal spectrum. This is especially true for photodiode array detectors. Spectra accurate to within 2 cm^{-1} of all but the weaker bands can be taken in a minute or less if desired (including the background spectrum). Using pulsed, or higher intensity continuous wave (CW) lasers, spectra could be taken in less time with even better signal to noise ratios.

The vacuum pyrolysis studies of Halon 2402 revealed four products: Halon 1301 (bromotrifluoromethane), Halon 1202 (dibromodifluoromethane), bromine, and Halon 2400 (tetrafluoroethylene). Raman spectra of these four species in the gas phase at low pressures (about 50 Torr) are shown in Figures 56-59. A vapor-phase Raman spectrum of Halon 2402 is presented in Figure 60. The spectrum of pyrolyzed Halon 2402, showing all of these materials, is shown in Figure 61. A good match has been made between the Raman spectra of the four products and that of pyrolysed Halon 2402. The vacuum pyrolysis spectrum of Halon 2402 contains three vibrational frequencies (peaks) which could not be assigned to any of the above products. These peaks were later assigned to silicon compounds (fluorinated siloxanes and polymers) formed from interaction of the hot gases with the quartz pyrolysis tube. Raman spectra of these silicon compounds are not available and exact identification is not possible.

The second experiment, utilizing nitrogen as a carrier gas to transfer Halon 2402 and the decomposition products, accurately reproduced the
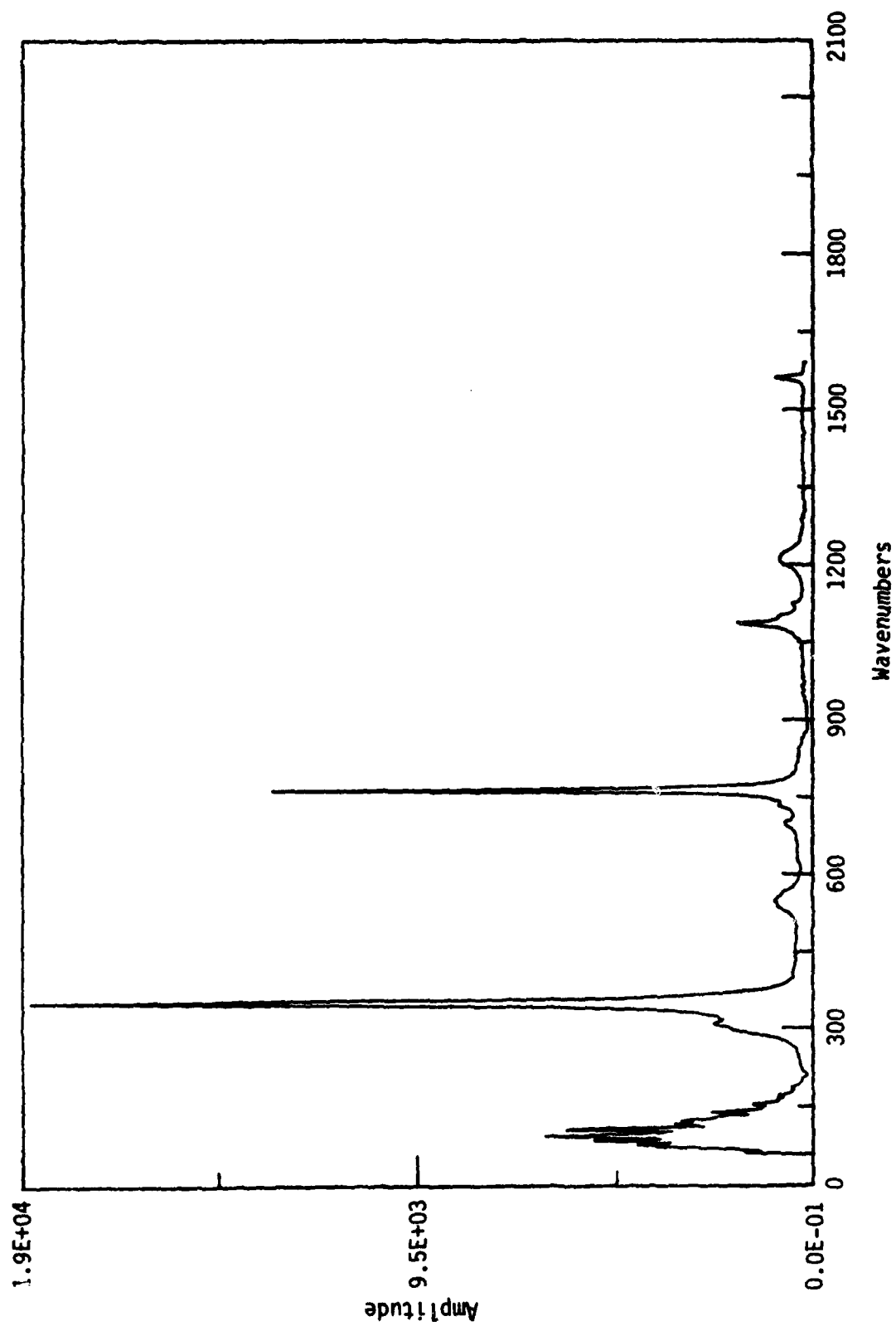
Figure 56. Raman Spectrum of Halon 1301, Bromotrifluoromethane, CF_3Br, in the Gas Phase.

174
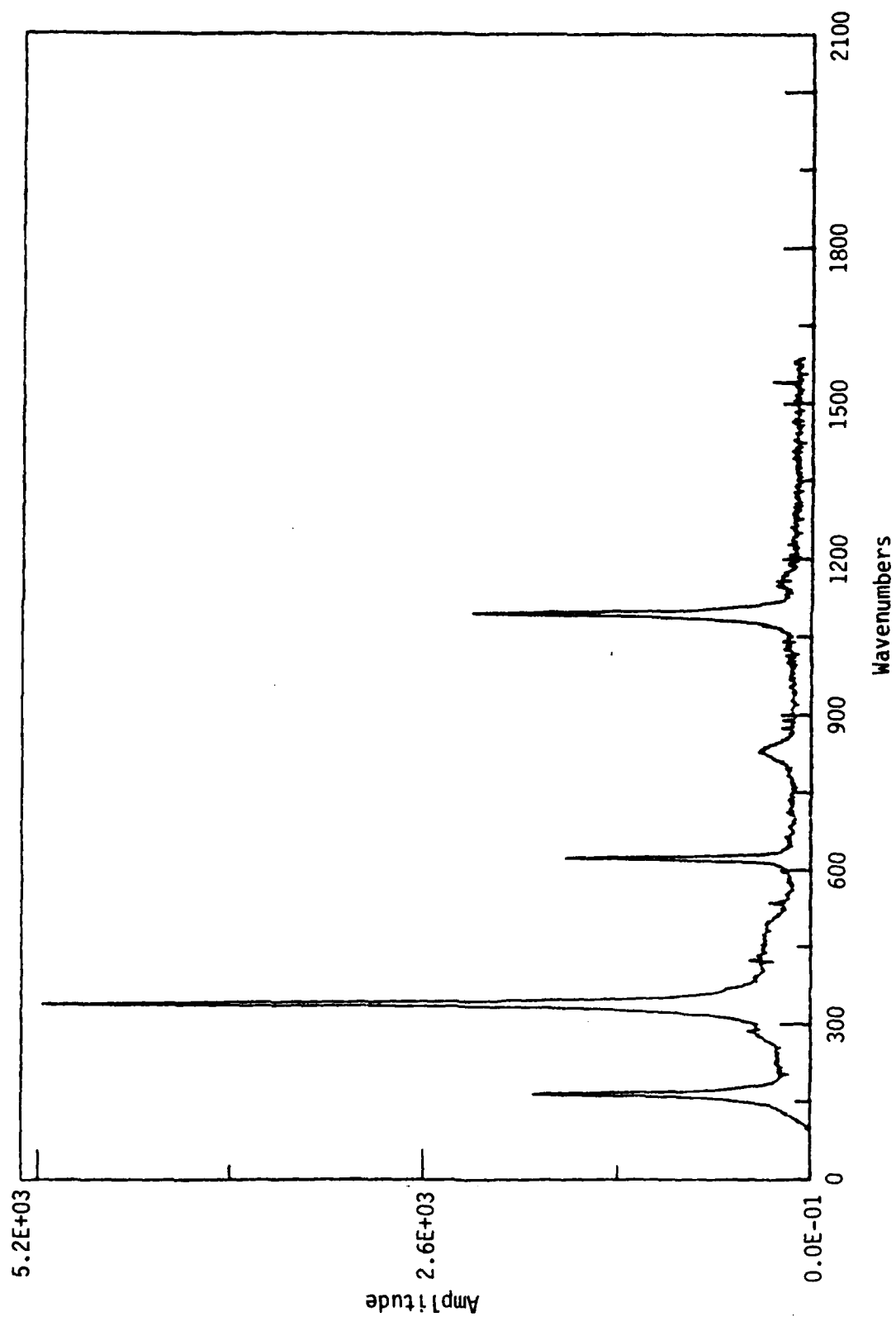
Figure 57. Raman Spectrum of Halon 1202, Dibromodifluoromethane, CBr_2F_2, in the Gas Phase.
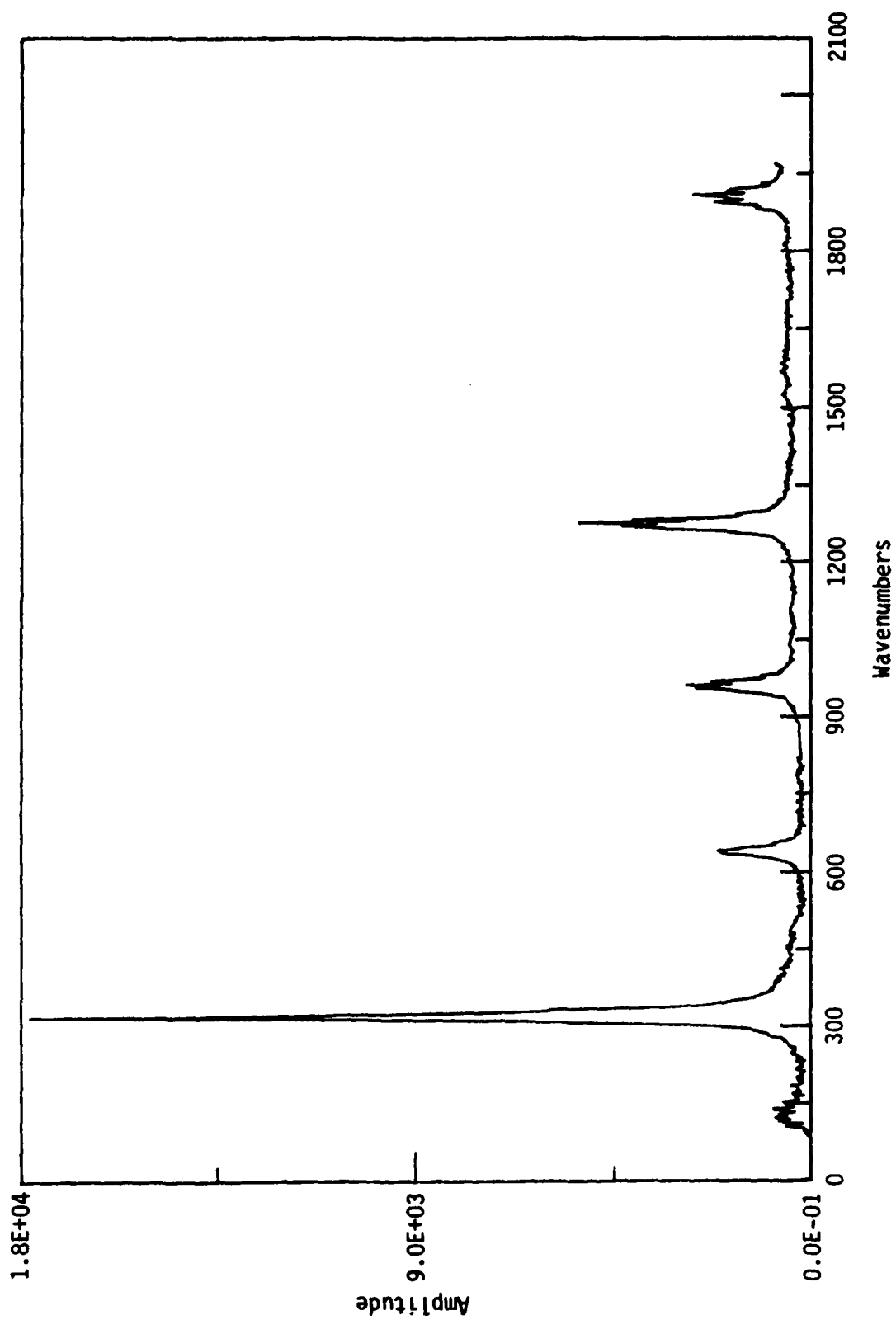
Figure 58. Raman Spectrum of Diatomic Bromine, Br_2, in the Gas Phase.

176
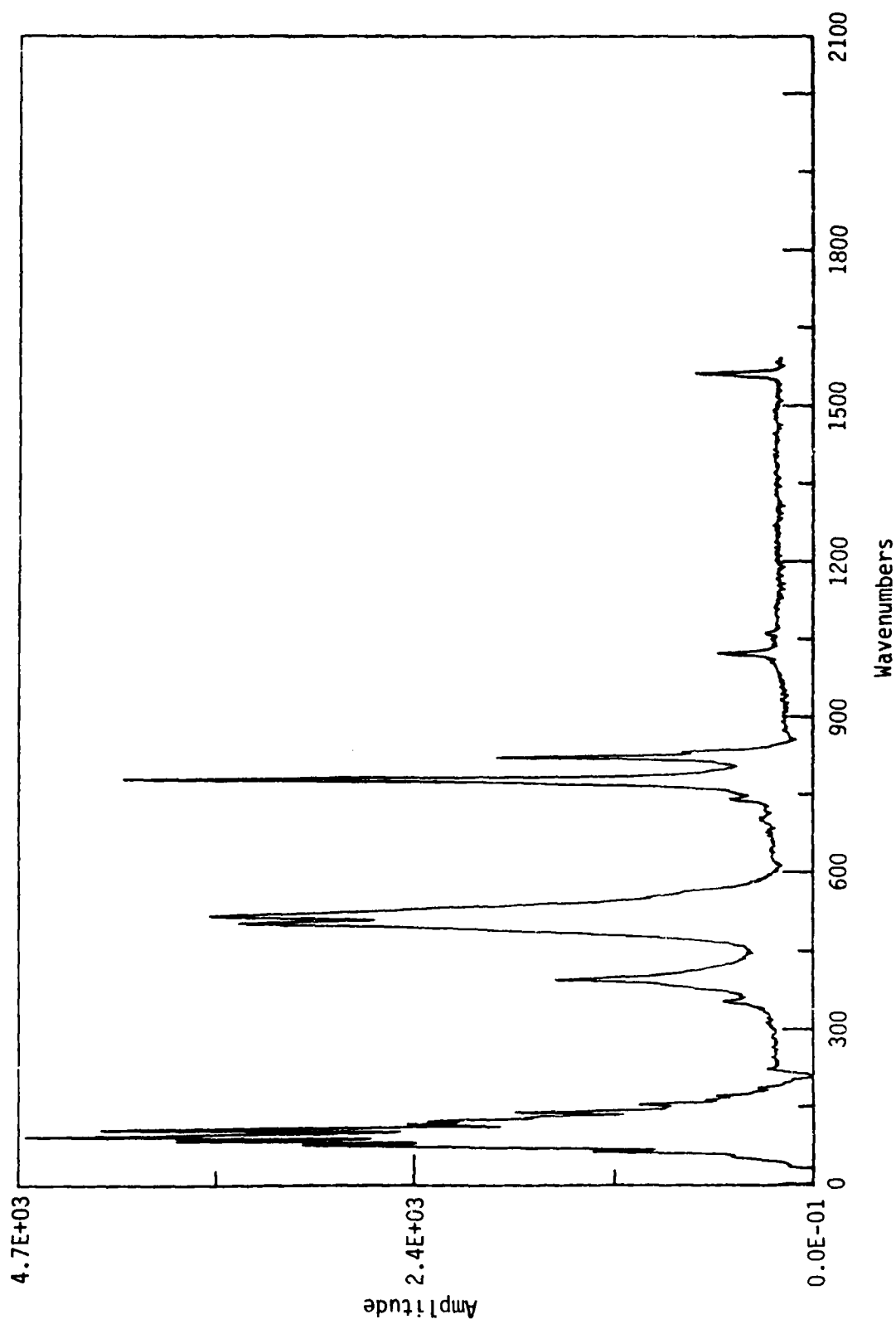
Figure 59. Raman Spectrum of Halon 2400, Tetrafluoroethene, C_2F_4, in the Gas Phase.

177
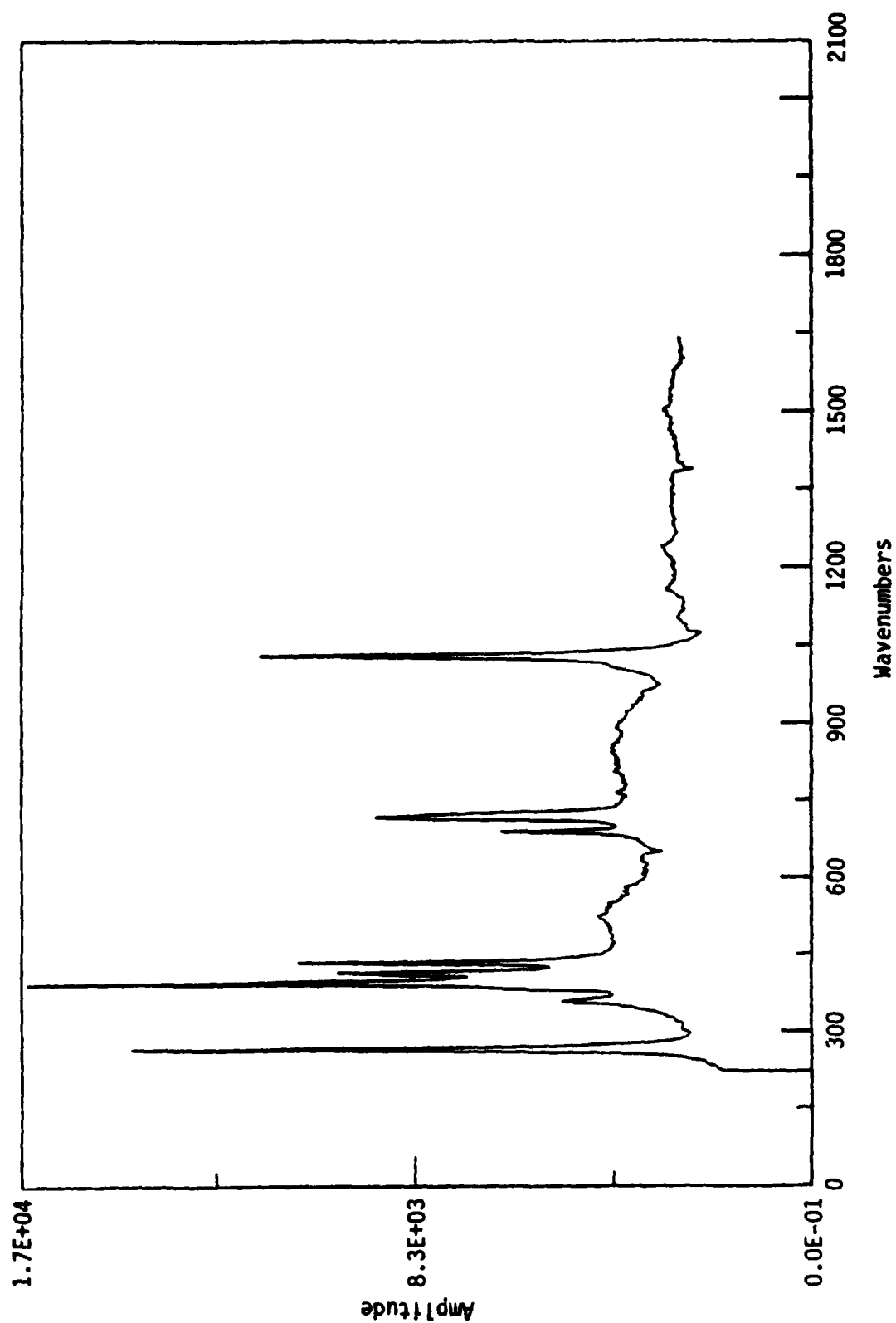
Figure 60. Raman Spectrum of Halon 2402, Dibromotetrafluoroethane, $C_2Br_2F_4$, in the Gas Phase.

178
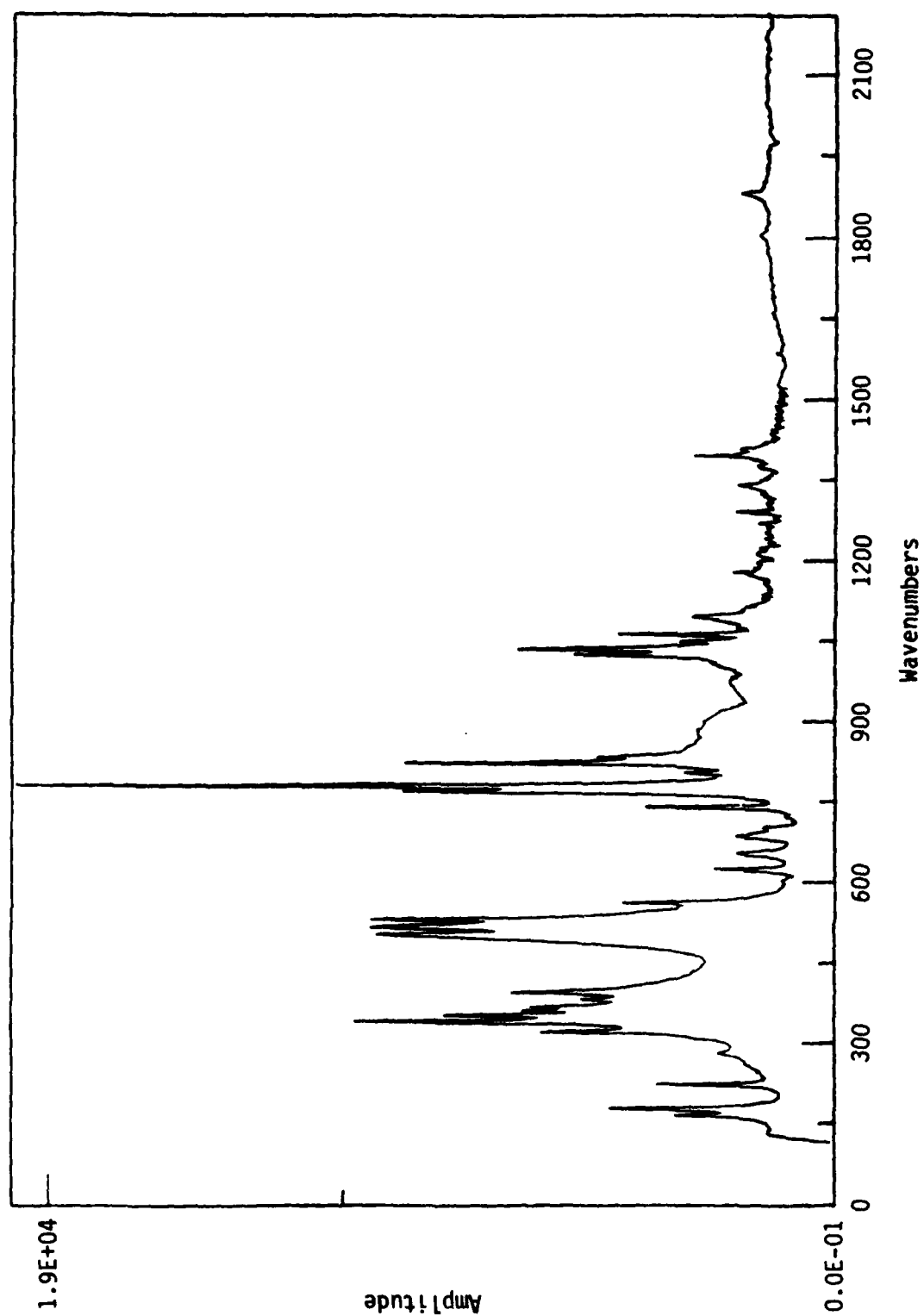
Figure 61. Raman Spectrum of Vacuum Pyrolysis Products of Halon 2402.

179

vacuum pyrolysis experiment; however, significantly larger amounts of silicon compounds were also observed. During the third experiment, with oxygen as the carrier gas, large amounts of silicon compounds were formed.

c. Concentrations in an Outdoor Fire

Grab samples were collected during the large-scale pit tests discussed earlier in this report. The sampling apparatus (Thermal Gas Device [TGD]) for combustion gases consisted of the following parts: sample probe, probe support, grab sample section, and suction blower. The probe was a 3-inch pipe in two sections, connected by flanges. The support tower was constructed primarily from nominal 2-inch stainless steel angles. Some aluminum angles were added later for additional support. The aluminum sections melted owing to the intense heat generated during the large-scale pit fires. The sampling section was a short section of pipe with openings and fittings for eight grab-sample cylinders (only seven were used in these tests). All pipe was welded 316 stainless steel. The nominal 2-inch and 3-inch pipe was SCH 40.

The upper section of the sample pipe was nominal 3-inch welded steel. At the upper end of the probe was a 120-degree bend with approximately a 76 cm (30-inch) radius. When the probe was angled up at 30 degrees, the open end was pointed directly down. The total length of the upper section was 5.84 meters (19.2 feet). At the lower end of this section, a four-bolt, 150-pound flange was welded on. The unbent portion of this section was approximately 4.19 meters (13.75 feet).

The flanges were all 316 stainless steel using four nominal 3/4-inch bolts. The lower section of the probe was flanged at both ends, had a short radius, and had a 30-degree bend at the bottom to become level with the rest of the sample apparatus. The grab sample section was a nominal 3-inch pipe, 0.762 meters (2.5 feet) long, flanged at both ends. It had four holes per side, spaced 15.2 cm (6 inches) apart, with fittings for the evacuated cylinders. The cylinder connections were nominal 1/8-inch pipe nipples, welded to 1/4-inch pipe fittings, and extended into the 3-inch pipe about 1.90 cm (3/4 inches). All fittings were 316 SS.

Flow measurements with the entire TGD gave a linear velocity of about 305 m/min (1000 ft/min) which corresponds to a volumetric flow rate of 1416 L/min (50 ft^3/min), near to the maximum rating of 1472 L/min (52 ft^3/min) for the blower. A nominal 2-inch pipe coupling was welded to the reducer to connect to the section leading to the blower. The section leading to the blower was a 6.1 meter (20-foot), 2-inch diameter pipe, threaded at both ends. At the front, the pipe was connected to a 90-degree ell, to a short pipe nipple, to another ell, and then to the pipe coupling. This allowed the main TGD unit to be lowered, as the two elbows formed a joint or hinge, which rose to form an angle in the piping at this point.

The main vacuum was supplied by a totally enclosed, fan-cooled, 1 lb/in.^{2} rated, 1/2 horsepower, 115/230 volt, single-phase GAST blower. At the initial design rate of 708 L/min, the blower was able to generate 56.0 Torr (30 inches of water) vacuum. Some operating characteristics of the blower are as follows:

1472 L/min (52 ft^3/min)	0 Torr (0 inches water)
1359 L/min (48 ft^3/min)	11.2 Torr (6 inches water)
708 L/min (25 ft^3/min)	56.0 Torr (30 inches water)

The solenoids were fired at random times before (controls) and during extinguishment. Because the wind and firefighters shifted continuously during the test, the concentrations of materials in the grab samples will vary widely. In Test 3, a request was made to keep the extinguishment as near to the sample probe as possible. For this reason, the concentrations of Halon 2402 in that test may be unrealistically large. Three types of grab sample containers were used and may be identified from the sample number. Type "A" containers are thin-wall stainless steel with a volume of 1800 mL and a special anodized interior surface. These containers were obtained from the U.S. Environmental Protection Agency. Type "B" containers are aluminum and have a volume of 1190 mL. The type "C" cylinders are heavy stainless steel with a volume of 1 liter.

The samples were tested for free halon (1211 in Test 1 and 2402 in Tests 2 and 3), hydrohalic acid (HCl, HBr, and/or HF), and halogens (F$_2$, Br$_2$, Cl$_2$).

The Halon 1211 test samples (Test 1) were analyzed on the HP 5890 GC with an FID. The following parameters were used: detector temperature, 250 °C; injection port temperature, 200 °C; oven temperature, 100 °C (isothermal); column flow rate, 1 mL/min (He); total flow rate including makeup gas, 30 mL; hydrogen flow rate, 30 mL/min; airflow rate, 450 mL/min; split ratio, 50:1. Head gas in a cylinder of Halon 1211 was used as a standard and gave a value of $5.073 \pm 0.192 \times 10^6$ AU for a 100 µL injection. The samples were run with injections of 100 µL each.

The Halon 2402 analyses were run on the HP 5890 GC with the electron capture detector. The sample containers were pressurized to 214 to 241 Torr (4 to 4.5 lb/in^2) over atmospheric pressure with nitrogen gas prior to removal of 50 µL aliquots. The following GC parameters were used: column pressure, 120 kPa; column flow rate, 0.79 mL/min; total (column plus makeup gas) flow rate, 40 mL/min; split vent flow rate, 153 mL/min; split ratio, 195; oven temperature, 35 °C isothermal; injection port temperature, 100 °C; detector temperature, 150 °C. The gas chromatographic analyses, even with an electron capture detector, showed no carbon-containing halon decomposition products.

The grab sample containers were washed out with 110 to 159 mL of distilled water. The free acids were determined for the washings using a specific ion electrode. The free halogens were determined by titration with 0.1 N sodium thiosulfate following liberation of iodine. In all cases, the final concentrations were adjusted to reflect concentrations in the gas phase in volumetric units by taking into account the container and washing volumes. This calculation requires that all of the acids and halogens entering the grab sample container be obtained in the washing. The results are in Table 42.

3. Discussion

Few studies have been performed on Halon 2402 decomposition products in real fire situations. Toxicity of pyrolysis products has been reported to increase in the order of Halon 1301, 1211, 2402 (Reference 31). For Halon 1301, concentrations of HBr and HF approach 30 ppm in postfire environments with fires extinguished in approximately 10 seconds (Reference 43). For long-burning fires, concentrations of HBr and HF approached 300 ppm. With Halon

TABLE 42. DECOMPOSITION PRODUCTS IN LARGE-SCALE PIT TESTS.

Test	Sample	Halon,[a] ppm	HF	HBr	Halogen,[b] ppb
			Concentration		
			Hydrogen halide, ppb		
1(1211)	B4, control	0	4	3	19
	B5	885 ± 28	28	16	41
2(2402)	A15, control	0[c]	2	<1	0
	B12	84 ± 12	49	1	81
	B11	207 ± 10	22	29	0
	A1	150 ± 3	24	3	14
	A13	2005 ± 52	130	5	0
3(2402)	C28, control	0	513	31	33
	A17	675 ± 31	16	3	0
	A22	2 ± 1	256	67	24
	A49	d	30	12	0
	A48	0	4	1	119
	A27	0	6	<1	0
	A24	0	25	2	15

[a]Standard deviations for 3 to 6 samples are given.

[b]Total halogen expressed as diatomic bromine in the gas phase.

[c]This control sample was analyzed with the FID.

[d]This results of this analysis were discarded owing to obvious contamination during the gas chromatography.

1301, and presumably Halon 2402, byproducts of minor concern for rapidly extinguished fires; however, for long extinguishment, large and dangerous levels of decomposition could be reached. In general, however, personnel will have already been evacuated from hot, sustained fires. In the outdoor, large-scale pit fire sampled in the studies reported here, the inorganic decomposition products were present in very small, parts-per-billion (ppb), concentrations.

Free halogens and hydrogen halides are the most toxic products of halon decomposition; however, the Raman spectral data show that organic products are also present. Tube pyrolysis studies have shown that contact times of 1 second in a stainless steel tube at 400 °C gives 7 percent decomposition of Halon 2402 while contact with a stainless steel tube at 800 °C for the same amount of time gives 100 percent decomposition (Reference 37). Modeling extinguishment by spraying a hot metal plate with Halon 2402 gives 0.3 to 2.5 percent decomposition, an amount much less than that obtained in tube pyrolysis (Reference 37). Concentrations of 55 to 120 ppm hydrogen fluoride were determined depending on discharge rate and the type of metal in the metal plate. The concentration of Br- (presumably as HBr) was considerably less (5 to 10 ppm). The highly toxic products were bromine, carbonyl halides, and carbon monoxide. These tests also showed that the amount of decomposition products depends upon the discharge--the higher the discharge rate (i.e., the faster the extinguishment), the lower the decomposition.

Sampling of the enclosed fire showed no carbon-containing halogen compounds down to the ppm range. The analyses did, however, show that the concentrations of Halon 2402 required to extinguish fires indoors can reach dangerous levels. Moreover, in an enclosed area, the Halon 2402 concentration varies widely following extinguishment. Two trends were noticed in the enclosed fire tests. First, the concentrations of Halon 2402 in the vicinity of the fire tended to be lower than elsewhere within the room. Second, the concentration appeared to reach a minimum in the corners. The apparent decrease in concentration near the fire may be due to buoyancy and air circulation induced by heating.

It is obvious that control sample C28 for the large-scale pit fires had been contaminated at some point. Nevertheless, the amounts of halogen and hydrogen halide in the fire are known, from this test, to be extraordinarily

small. They are all in the ppb range. These are maximum amounts. Hydrogen halide can also arise from hydrolysis of halon during the storage time in the grab sample. This does not seem to have occurred, however, since there is little correlation between the halon and hydrogen halide concentrations.

4. Conclusions

a. The concentrations of simple inorganic halogen-containing products of Halon 2402 decomposition are unlikely to reach seriously toxic levels during real fire situations. In the case of extremely long-lived fires, this may no longer be true.

b. Carbon-containing halogen compounds, other than free Halon 2402, are unlikely to be formed in dangerous quantities. None were detected, down to the ppb level, in any of the testing reported in this unit.

c. The use of artificial pyrolysis by hot metal plates or heated tubes does not simulate the quantities of toxic materials actually produced in realistic situations.

d. The concentrations of Halon 2402 required to extinguish an enclosed fire are likely to reach dangerously toxic levels. Moreover, the distribution of Halon 2402 within a room following extinguishment of a fire is highly heterogeneous. The lowest concentrations for inside extinguishment may occur near the extinguished fire and in corners.

E. DISPERSION

1. Objectives

To assess environmental problems resulting from Halon 2402 spills and use, atmospheric dispersion methods were developed and selected calculations were performed. Two different approaches were used. In the first, the procedure of Turner (Reference 44) was used to develop an atmospheric dispersion computer program to generate concentration grids downwind of a continuous source. The second approach uses the method of Kahler (Reference 45) to determine toxic corridors.

2. Experimental

a. Dispersion Grid Calculation

A simple Gaussian plume model, essentially that of Turner (Reference 44), was employed in this series of calculations. The accuracy of such a model to predict concentrations of materials downwind of spills and releases depends on several conditions. First, the terrain must be flat or gently rolling. Second, there must be no obstructions (buildings, etc.) near the source. Third, the wind direction and velocity must be constant and uniform.

Only ground-level releases were considered, although Turner's method is sufficiently powerful to handle aboveground sources. The general dispersion equation for such a release is

$$\chi = (Q/\Pi\sigma_y\sigma_z U)e^{[-0.5(y/\sigma_y)^2]} \tag{26}$$

where χ is the concentration, U is the wind velocity, y is the perpendicular distance from the plume centerline, q is the source strength, and σ_z and σ_y are the vertical and horizontal dispersion coefficients. If the source strength has units of g/s, the wind velocity is in m/s, and the distance and dispersion coefficients are in meters, the concentration will have units of g/m^2.

Turner gives graphs for estimating the dispersion coefficients as functions of distance downwind from the source (Reference 44). The particular plot to use depends on the stability category (i.e., how stable the turbulent structure of the air is). In Turner's notation, these categories are given the letters A (the most unstable) through F (the most stable). The stability category can be estimated from the degree of cloudiness, whether the spill occurs during the day or at night, the wind velocity, and the amount of solar radiation. The computer program uses the percent cloud cover, the solar angle (the angle of the sun from the horizon), the wind velocity, and the time of spill (day or night) to determine the proper stability category.

186

Values of σ_y are calculated from equations obtained from best fits to log/log plots. The values of σ_z are obtained from interpolation of data taken from graphs. The BASIC program (Table 43) is interactive and can be used for any gaseous material for which a source rate is known. A copy of an example input is presented in Table 44. The concentration output can be put on a mass-per-unit-volume or a volume-fraction basis. In order to calculate volume-fraction concentrations, the temperature, atmospheric pressure, and molecular weight (259.83 for Halon 2402) must be known. This information is not needed for mass-per-unit-volume concentrations. The program automatically selects the units (for example mg/m^3 or ppm) to give numbers of the proper size. A grid output gives concentrations as a function of x and y coordinates with the origin at the source.

An example output with concentrations expressed as fractions by volume is shown in Table 45. This particular example is for a flow rate of 8989 kg/h (5.5 lb/s) from a nozzle onto a fire or a warm surface where evaporation takes place immediately. At the centerline of the plume, the concentration of Halon 2402 is 120 ppm and the concentration along this line decreases with increasing distance. The plume spreads so that off the centerline, the concentration increases and then decreases with time. This particular table shows that with a relatively high Halon 2402 flow rate, individuals downwind at a distance of 100 meters (328 feet) would not exceed the 500 ppm 10-minute U.S. Military recommended level. Note, however, that this calculation was performed for a clear day with high solar radiation, conditions which give a "B" stability category (relatively unstable). For more stable conditions, the concentrations would be considerably higher.

An example of mass-per-unit-volume output from "PLUME" for evaporation of Halon 2402 at 1500 kg/h is shown in Table 46. Here the output automatically changes from mg/m^3 to $\mu g/m^3$ to keep the numbers reasonable.

Table 47 gives Halon 2402 concentrations along the plume centerline at a distance of 100 meters for a variety of initial conditions. The grid output containing these data are in Tables G-1 through G-12, Appendix G. The concentration does not always decrease with increasing wind

187

TABLE 43.   SOURCE LISTING FOR BASIC COMPUTER PROGRAM "PLUME."

```
CLS
'THIS PROGRAM GENERATES PLUME CONCENTRATIONS USING RELATIONS IN TURNER'
DIM XX(100), Y(100), X(100), CHI(100),STORE(100), XZ(100)
INPUT "DESIRED OUTPUT IN MASS/VOLUME (1) OR VOLUME/VOLUME (2)";CN
IF CN <>1 AND CN<>2 THEN PRINT "ENTER 1 OR 2":GOTO 40
INPUT "SOURCE STRENGTH IN KG/HOUR = ";QQ
IF QQ<=0 THEN PRINT "SOURCE STRENGTH MUST BE NONZERO, POSITIVE NUMBER":GOTO
70
Q=QQ * (1000!/3600)
MULT=0:MU=0
00 INPUT "WIND VELOCITY IN METERS/SECOND = ";U
10 IF U<=0 THEN PRINT "WIND VELOCITY CANNOT BE ZERO OR NEGATIVE":GOTO 100
20 IF CN=1 THEN 190
30 INPUT "TEMPERATURE IN CELSIUS = ";TEMP
40 INPUT "ATMOSPHERIC PRESSURE IN TORR = ";PRESS
50 IF PRESS<=0 THEN PRINT "PRESSURE CANNOT BE ZERO OR NEGATIVE":GOTO 140
60 INPUT "MOLECULAR WEIGHT = ";MW
70 IF MW <=0 THEN PRINT "MOLECULAR WEIGHT MUST BE POSITIVE, NONZERO":GOTO 160
80 STDVOL = .022414*((TEMP + 273.15)/273.15)*(760/PRESS)
90 INPUT "DAY (D) OR NIGHT (N)";DN$
00 IF DN$ = "D" THEN DN$ = "DAY":GOTO 240
10 IF DN$ = "N" THEN DN$ = "NIGHT":GOTO 240
20 PRINT "ENTER 'D' OR 'N'"
30 GOTO 190
40 INPUT "CLOUD COVER PERCENTAGE (0 TO 100%) = ";P
50 IF P<0 OR P>100 THEN PRINT "PERCENTAGE MUST BE 0 TO 100":GOTO 240
60 IF P>=90 THEN SC$ = "D": GOTO 540
70 IF DN$ = "DAY" THEN 330
80 IF P>44 AND U > 3 THEN SC$ = "D": GOTO 540
90 IF P>44 THEN SC$ = "E": GOTO 540
00 IF U>5 THEN SC$ = "D": GOTO 540
10 IF U>3 THEN SC$ = "E": GOTO 540
20 SC$ = "F": GOTO 540
30 INPUT "SOLAR RADIATION ANGLE (0 TO 90; EXACT VALUE NOT NECESSARY) = ";ANG
40 IF ANG < 35 THEN 500
```

```
350 IF ANG < 60 THEN 390

360 IF P < 10 THEN 410

370 IF P < 70 THEN 450

380 GOTO 500

390 IF P < 10 THEN 450

400 GOTO 500

410 'STRONG SOLAR RADIATION'

420 IF U > 5 THEN SC$ = "C":GOTO 540

430 IF U > 2.5 THEN SC$ = "B":GOTO 540

440 SC$ = "A": GOTO 540

450 'MODERATE SOLAR RADIATION'

460 IF U > 5.5 THEN SC$ = "D": GOTO 540

470 IF U > 4! THEN SC$ = "C": GOTO 540

480 IF U > 2.5 THEN SC$ = "B": GOTO 540

490 SC$ = "A": GOTO 540

500 'SLIGHT' SOLAR RADIATION

510 IF U > 5 THEN SC$ = "D": GOTO 540

520 IF U > 2 THEN SC$ = "C": GOTO 540

530 SC$ = "B": GOTO 540

540 INPUT "STEP SIZE DOWNWIND (BETWEEN 0.1 AND 10 KM)";DX

550 X(0) = 0

560 INPUT "STEP SIZE CROSSWIND (BETWEEN 1 AND 1000 METERS)";DY

570 Y(0) = 0

580 XX(0) = 0

590 FOR I% = 1 TO 16

600 READ XX (I%)

610 NEXT I%

620 FOR I% = 1 TO 85

630 READ STORE(I%)

640 NEXT I%

650 IF SC$ = "F" THEN ST% = 0:M% = 16: A = 3.466923: B = .903606: GOTO 720

660 IF SC$ = "E" THEN ST% = 16:M% = 16: A = 3.872389: B = .902606: GOTO 720

670 IF SC$ = "D" THEN ST% = 32:M% = 16: A = 4.158014: B = .9027128: GOTO 720

680 IF SC$ = "C" THEN ST% = 48:M% = 16: A = 4.589754: B = .8998834: GOTO 720

690 IF SC$ = "B" THEN ST% = 64:M% = 13: A = 4.969314: B = .8815534: GOTO 720
```

```
700 IF SC$ = "A" THEN ST% = 77:M% = 8: A = 5.294939: B = .8681988: GOTO 720
710 IF A = 0 THEN PRINT "ERROR IN ASSIGNING STABILITY CATEGORY":GOTO 1420
720 XZ(0) = 0!
730 FOR I% = 1 TO M%
740 XZ(I%) = STORE (I% + ST%)
750 NEXT I%
760 PRINT "       ";
770 FOR I% = 1 TO 9
780 Y(I%) = Y(I%-1) + DY
790 NEXT I%
800 CLS
810 LPRINT "SOURCE STRENGTH = ";QQ;"KILOGRAMS/HOUR (";Q;"GRAMS/SECOND)"
820 LPRINT "WIND VELOCITY = ";U;"METERS/SECOND (";2.2369363#*U;"MILES/HOUR)"
830 LPRINT DN$; "WITH CLOUD COVER = ";P;"PERCENT"
840 IF DN$ = "DAY" THEN LPRINT "SOLAR ANGLE = ";ANG;"DEGREES"
850 LPRINT "STABILITY CATEGORY = ";SC$
860 IF CN = 2 THEN LPRINT "TEMPERATURE = ";TEMP;"DEGREES CELSIUS"
870 IF CN = 2 THEN LPRINT "PRESSURE = ";PRESS;"TORR"
880 IF CN = 2 THEN LPRINT "MOLECULAR WEIGHT = ";MW
890 LPRINT
900 LPRINT:LPRINT"           ";
910 FOR I% = 0 TO 9
920 LPRINT USING "####";Y(I%);:LPRINT" m ";
930 NEXT I%
940 FOR I%=1 TO 33
950 X(I%)=X(I%-1) + DX
960 IF SC$ = "A" AND X(I%)>3 THEN 1410
970 IF SC$ = "B" AND X(I%)>30 THEN 1410
980 IF X(I%) > 100 THEN 1410
990 LSIGY = A + B*LOG(X(I%))
1000 SIGY=EXP(LSIGY)
1010 SIGY=EXP(LSIGY)
1020 FOR J% = 1 TO 16
1030 IF X(I%) < XX(J%) THEN N% = J%: GOTO 1060
1040 NEXT J%
```

```
1050 GOTO 1420
1060 DSIG = XZ(N%)=XZ(N%-1)
1070 DXX = XX(N%)-XX(N%-1)
1080 DEL = XX(N%)-X(I%)
1090 SIGZ = XZ(N%) - DSIG*(DEL/DXX)
1100 FOR J% = 0 TO 9
1110 CHI(J%)= Q/(3.14159 * SIGZ * SIGY * U))*EXP(-.5*(Y(J%)/SIGY)^2)
1120 CHI(J%) = CHI(J%) * 1!
1130 IF CN=1 THEN 1150
1140 CHI(J%) = (CHI(J%)/MW)*STDVOL*100
1150 NEXT J%
1160 IF CN=2 AND CHI(0)>=1 THEN MU=1:IF MU<>MULT THEN LPRINT:LPRINT
     "CONCENTRATION IN PERCENT BY VOLUME":LPRINT:MULT=MU
1170 IF CN=2 AND CHI(0)<1 AND CHI(0)>=.1 THEN MU=10:IF MU<>MULT THEN
     LPRINT:LPRINT "                    CONCENTRATION IN PARTS PER THOUSAND BY
     VOLUME":LPRINT:MULT=MU
1180 IF CN=2 AND CHI(0)<.1 AND CHI(0) >=.0001 THEN MU-10000:IF MU<>MULT THEN
     LPRINT:LPRINT "                  CONCENTRATION IN PPM BY VOLUME":LPRINT:MULT=MU
1190 IF CN=2 AND CHI(0)<.0001 THEN MU=1E+07: IF MU<>MULT THEN LPRINT:LPRINT "
              CONCENTRATION IN PPB BY VOLUME":LPRINT:MULT=MU
1200 IF CN=1 AND CHI(0)>=1 THEN MU=1:IF MU<>MULT THEN LPRINT:LPRINT "
         CONCENTRATION IN GRAMS/CUBIT METER":LPRINT:MULT=MU
1210 IF CN=1 AND CHI(0)<1 AND CHI(0)>=.001 THEN MU=100:IF MU<>MULT THEN
     LPRINT:LPRINT "                 CONCENTRATION IN MILLIGRAMS/CUBIC
     METER":LPRINT:MULT=MU
1220 IF CN=1 AND CHI(0)<.001 AND CHI(0)>=.000001 THEN MU=1000000!:IF MU<>MULT
     THEN LPRINT:LPRINT "                 CONCENTRATION IN MICROGRAMS/CUBIC
     METER":LPRINT:MULT=MU
1230 IF CN=1 AND CHI(0)<.000001 AND CHI(0)>=1E-09 THEN MU=1E+09:IF MU<>MULT
     THEN LPRINT:LPRINT "                 CONCENTRATION IN NANOGRAMS/CUBIC
     METER":LPRINT:MULT=MU
1240 IF CN=1 AND CHI(0)<1E-09 THEN MU=1E+12:IF MU<>MULT THEN LPRINT:LPRINT "
              CONCENTRATION IN NANOGRAMS/CUBIC METER":LPRINT:MULT=MU
1250 IF CN=1 AND CHI(0)<1E-09 THEN MU=1E+12:IF MU<>MULT THEN LPRINT:LPRINT "
              CONCENTRATION IN NANOGRAMS/CUBIC METER":LPRINT:MULT=MU
```

TABLE 43. SOURCE LISTING FOR BASIC COMPUTER PROGRAM "PLUME" (CONCLUDED).

```
1260 LPRINT USING "###.#";X(I%);:LPRINT" KM ";
1270 FOR J%=0 TO 9:LPRINT USING "####.##";CHI(J%)*MULT;:LPRINT"";:NEXT J%
1280 LPRINT ""
1290 NEXT I%
1300 DATA 0.1, 0.2, 0.3, 0.4, 0.5, 1, 2, 3, 4, 5, 10, 20, 30, 40, 50, 100
1310 DATA 2.30, 4.05, 5.58, 7.03, 8.45, 13.9 21.6, 26.6, 30.4, 33.8, 46.5
1320 DATA 59.5, 67.5, 73.5, 78.0, 93
1330 DATA 3.50, 6.30, 8.70, 10.9, 12.9, 21.5, 33.6, 42.5, 49.8, 55.8, 77.9
1340 DATA 110, 130, 144, 154, 184
1350 DATA 4.60, 8.55, 12.1, 15.4, 18.5, 31.5, 49.8, 64.5, 77.0, 87.5, 136
1360 DATA 202, 253, 294, 328, 455
1370 DATA 7.35, 13.8, 20.1, 26.1, 32.4, 60.4, 113, 168, 218, 268, 505, 950
1380 DATA 1380, 1780, 2180, 3870
1390 DATA 10.8, 20.2, 30.1, 40.5, 51.0, 109.5, 232, 362, 502, 645, 1350
1400 DATA 2870, 4450
1410 DATA 14.1, 29.4, 47.5, 73.0, 115, 455, 1950, 4450
1420 END
```

TABLE 44. EXAMPLE INTERACTIVE INPUT FOR COMPUTER PROGRAM "PLUME."

```
DESIRED OUTPUT IN MASS/VOLUME (1) OR VOLUME/VOLUME (2)? 2
SOURCE STRENGTH IN KG/HOUR = ? 1500
WIND VELOCITY IN METERS/SECOND = ? 3
TEMPERATURE IN CELSIUS = ? 20
ATMOSPHERIC PRESSURE IN TORR = ? 760
MOLECULAR WEIGHT = ? 259.83
DAY (D) OR NIGHT (N)? D
CLOUD COVER PERCENTAGE (0 TO 100%) = ? 0
SOLAR RADIATION ANGLE (0 TO 90; EXACT VALUE NOT NECESSARY) = ? 90
STEP SIZE DOWNWIND (BETWEEN 0.1 AND 10 KM)? .1
STEP SIZE CROSSWIND (BETWEEN 1 AND 1000 METERS)? 100
```

TABLE 45. VOLUME/VOLUME CONCENTRATIONS OF HALON 2402 CALCULATED FOR A FLOW RATE OF 8989 kg/h AND A WIND SPEED OF 3 m/s BY COMPUTER PROGRAM "PLUME."

SOURCE STRENGTH = 8989 kg/h (2496.945 g/s)

WIND VELOCITY = 3 m/s (6.7108089 mph)

DAY WITH CLOUD COVER = 0 PERCENT

STABILITY CATEGORY = B

TEMPERATURE = 20

MOLECULAR WEIGHT = 259.83

	0 m	100 m	200 m	300 m	400 m	500 m	600 m	700 m	800 m	900 m
CONCENTRATION IN ppm BY VOLUME										
0.1 KM	120.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.2 KM	34.86	0.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.3 KM	16.36	2.18	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.4 KM	9.44	2.80	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5 KM	6.16	2.71	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6 KM	4.26	2.35	0.40	0.02	0.00	0.00	0.00	0.00	0.00	0.00
0.7 KM	3.14	1.99	0.51	0.05	0.00	0.00	0.00	0.00	0.00	0.00
0.8 KM	2.41	1.68	0.58	0.10	0.01	0.00	0.00	0.00	0.00	0.00
0.9 KM	1.91	1.43	0.60	0.14	0.02	0.00	0.00	0.00	0.00	0.00
1.0 KM	1.56	1.22	0.59	0.18	0.03	0.00	0.00	0.00	0.00	0.00
1.1 KM	1.29	1.05	0.57	0.21	0.05	0.01	0.00	0.00	0.00	0.00
1.2 KM	1.08	0.91	0.54	0.22	0.07	0.01	0.00	0.00	0.00	0.00
CONCENTRATION IN ppb BY VOLUME										
1.3 KM	924.63	794.26	503.45	235.47	81.27	20.70	3.89	0.54	0.06	0.00
1.4 KM	799.21	699.43	468.80	240.65	94.61	28.49	6.57	1.16	0.16	0.02
1.5 KM	698.10	620.34	435.29	241.18	105.52	36.46	9.95	2.14	0.36	0.05
1.6 KM	615.34	553.79	403.68	238.34	113.97	44.14	13.85	3.52	0.72	0.12
1.7 KM	546.72	497.32	374.32	233.13	120.14	51.23	18.08	5.28	1.27	0.25
1.8 KM	489.17	449.02	347.30	226.35	124.30	57.52	22.42	7.37	2.04	0.48
1.9 KM	440.40	407.42	322.57	218.57	126.75	62.91	26.72	9.71	3.02	0.80

TABLE 45. VOLUME/VOLUME CONCENTRATIONS OF HALON 2402 CALCULATED FOR A FLOW RATE OF 8989 kg/h AND A WIND SPEED OF 3 m/s BY COMPUTER PROGRAM "PLUME" (CONCLUDED).

	0 m	100 m	200 m	300 m	400 m	500 m	600 m	700 m	800 m	900 m
CONCENTRATION IN ppb BY VOLUME										
2.0 KM	398.70	371.34	300.00	210.24	127.80	67.39	30.82	12.23	4.21	1.26
2.1 KM	361.65	338.81	278.58	201.03	127.32	70.77	34.53	14.78	5.56	1.83
2.2 KM	329.63	310.40	259.18	191.90	125.99	73.35	37.86	17.33	7.03	2.53
2.3 KM	301.76	285.44	241.61	182.99	124.01	75.20	40.80	19.81	8.61	3.35
2.4 KM	277.34	263.40	225.65	174.37	121.54	76.42	43.34	22.17	10.23	4.26
2.5 KM	255.83	243.84	211.15	166.12	118.73	77.09	45.48	24.37	11.87	5.25
2.6 KM	236.77	226.40	197.95	158.24	115.66	77.30	47.24	26.39	13.48	6.30
2.7 KM	219.81	210.79	185.89	150.76	112.44	77.12	48.65	28.22	15.05	7.38
2.8 KM	204.63	196.75	174.87	143.68	109.13	76.63	49.74	29.84	16.55	8.49
2.9 KM	191.01	184.08	164.78	136.99	105.78	75.87	50.54	31.27	17.97	9.59
3.0 KM	178.73	172.62	155.51	130.68	102.43	74.90	51.08	32.50	19.28	10.67
3.1 KM	167.17	161.77	146.60	124.40	98.85	73.56	51.26	33.45	20.44	11.70
3.2 KM	156.72	151.93	138.42	118.51	95.36	72.11	51.25	34.23	21.48	12.67
3.3 KM	147.24	142.98	130.90	113.00	91.98	70.59	51.08	34.85	22.42	13.60
3.4 KM	138.61	134.80	123.98	107.83	88.70	69.00	50.77	35.32	23.24	14.46
3.5 KM	130.74	127.32	117.58	102.99	85.54	67.38	50.34	35.66	23.96	15.27

TABLE 46. MASS/VOLUME CONCENTRATIONS OF HALON 2402 CALCULATED FOR A FLOW RATE OF 1500 kg/h AND A WIND SPEED OF 3 m/s BY COMPUTER PROGRAM "PLUME."

SOURCE STRENGTH = 1500 kg/h (416.6667 g/s)

WIND VELOCITY = 3 m/s (6.7108089 mph)

DAY WITH CLOUD COVER = 0 PERCENT

STABILITY CATEGORY = B

	0 m	100 m	200 m	300 m	400 m	500 m	600 m	700 m	800 m	900 m
	CONCENTRATION IN mm/m³									
0.1 KM	21.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.2 KM	6.28	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.3 KM	2.95	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.4 KM	1.70	0.51	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5 KM	1.11	0.49	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6 KM	0.77	0.42	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.7 KM	0.57	0.36	0.09	0.01	0.00	0.00	0.00	0.00	0.00	0.00
0.8 KM	0.43	0.30	0.10	0.02	0.00	0.00	0.00	0.00	0.00	0.00
0.9 KM	0.34	0.26	0.11	0.03	0.00	0.00	0.00	0.00	0.00	0.00
1.0 KM	0.28	0.22	0.11	0.03	0.01	0.00	0.00	0.00	0.00	0.00
1.1 KM	0.23	0.19	0.10	0.04	0.01	0.00	0.00	0.00	0.00	0.00
1.2 KM	0.20	0.16	0.10	0.04	0.01	0.00	0.00	0.00	0.00	0.00
1.3 KM	0.17	0.14	0.09	0.04	0.01	0.00	0.00	0.00	0.00	0.00
1.4 KM	0.14	0.13	0.08	0.04	0.02	0.01	0.00	0.00	0.00	0.00
1.5 KM	0.13	0.11	0.08	0.04	0.02	0.01	0.00	0.00	0.00	0.00
1.6 KM	0.11	0.10	0.07	0.04	0.02	0.01	0.00	0.00	0.00	0.00

TABLE 46. MASS/VOLUME CONCENTRATIONS OF HALON 2402 CALCULATED FOR A FLOW
RATE OF 1500 kg/h AND A WIND SPEED OF 3 m/s BY COMPUTER PROGRAM
"PLUME" (CONCLUDED).

	0 m	100 m	200 m	300 m	400 m	500 m	600 m	700 m	800 m	900 m
CONCENTRATION IN mm/m^3										
1.7 KM	985.44	896.39	674.70	420.20	216.55	92.34	32.58	9.51	2.30	0.46
1.8 KM	881.69	809.34	625.99	407.98	224.04	103.67	40.42	13.28	3.68	0.86
1.9 KM	793.79	734.35	581.41	393.96	228.46	113.39	48.16	17.51	5.45	1.45
2.0 KM	718.64	669.31	540.73	378.94	230.35	121.46	55.56	22.04	7.59	2.26
2.1 KM	651.86	610.68	502.12	362.34	229.49	127.56	62.23	26.65	10.01	3.30
2.2 KM	594.14	559.48	467.16	345.89	227.09	132.20	68.25	31.24	12.68	4.56
2.3 KM	543.90	514.50	435.48	329.82	223.52	135.54	73.55	35.71	15.51	6.03
2.4 KM	499.89	474.77	406.73	314.30	219.07	137.74	78.11	39.96	18.44	7.67
2.5 KM	461.12	439.51	380.59	299.41	214.00	138.95	81.97	43.93	21.39	9.46
2.6 KM	426.77	408.08	356.79	285.22	208.48	139.33	85.14	47.57	24.30	11.35
2.7 KM	396.19	379.93	335.06	271.74	202.67	139.01	87.68	50.86	27.13	13.31
2.8 KM	368.84	354.63	315.20	258.98	196.71	138.12	89.65	53.79	29.84	15.30
2.9 KM	344.29	331.80	297.00	246.92	190.67	136.75	91.09	56.36	32.39	17.29
3.0 KM	322.15	311.13	280.30	235.54	184.63	135.00	92.07	58.57	34.76	19.24
3.1 KM	301.32	291.58	264.23	224.22	178.18	132.59	92.39	60.29	36.84	21.08
3.2 KM	282.48	273.85	249.49	213.62	171.89	129.98	92.38	61.70	38.73	22.84
3.3 KM	265.40	257.70	235.94	203.68	165.78	127.23	92.06	62.81	40.41	24.51
3.4 KM	249.84	242.97	223.46	194.36	159.88	124.38	91.50	63.67	41.89	26.07
3.5 KM	235.65	229.48	211.94	185.63	154.19	121.46	90.73	64.28	43.19	27.52

TABLE 47. HALON 2402 CONCENTRATIONS ALONG PLUME CENTERLINE AT 100 METERS.

Strength, kg/m³	Wind velocity, m/s	Conditions	Stability category	Concentration, ppm by volume
Source strength varied				
1500	3	Sunny, clear	B	20.0
1000	3	Sunny, clear	B	13.4
500	3	Sunny, clear	B	6.7
100	3	Sunny, clear	B	1.3
Wind velocity varied				
1500	1	Sunny, clear	A	32.2
1500	2	Sunny, clear	A	16.1
1500	3	Sunny, clear	B	20.0
1500	5	Sunny, clear	B	12.0
1500	10	Sunny, clear	C	13.5
Conditions varied				
1500	3	Overcast day	D	111.2
1500	3	Cloudy night	E	194.9
1500	3	Partly cloudy night	F	444.9
1500	1	Partly cloudy night	F	1330.0

speed owing to the attainment of difference stability conditions. On the other hand, the concentration does always decrease with decreasing source strength. At night, with a source strength close to the highest values calculated earlier for evaporation following the spill of a 208-liter (55-gallon) drum, it is quite possible to attain dangerous concentrations of Halon 2402. Note, however, that large evaporation rates are usually obtained only during the daytime.

b.   Toxic Corridor Calculations

Predictive calculations were needed to determine whether a planned task of extinguishing a 24.4-meter (80-foot) diameter JP-4 fuel fire with Halon 2402 could be performed without producing unacceptable exposure levels from either the halon for its combustion/decomposition products for personnel in the vicinity. The procedure used is described below. The procedure used can be adapted as a general method for other situations.

It was planned the halon would be discharged through two different nozzles at rates of 150 kg/min (5.5 lb/s) and 259 kg/min (9.5 lb/s). The atmospheric conditions assumed for the calculations were worst-case daytime conditions--overcast sky or broken clouds. An 8 km/h (5 mi/h) wind was assumed since tests of this size are not run for higher wind velocities. The test time and date selected was 10 a.m. on November 15.

The algorithm used to determine the toxic corridor, the area within which the concentrations of a toxic chemical are dangerous, was based upon that given by Kahler (Reference 45). This method is sometimes called "Method 2: Chemical and Diffusion Factors." The input data required include:

(1) Source strength, Q lb/min.*

(2) Temperature difference between heights of 1.8 and 16.5 meters (6 and 54 feet), ΔT °F.

(3) Exposure limit, CP.

(4) Gram-molecular weight (GMW) of the toxic chemical.

(5) Mean wind direction (degrees).

---

* Kahler's method (Reference 45) requires inputs and outputs in English units. Since the equations used are unit-specific, the tabulated input and output recorded in this report are kept in English units.

199

(6) Wind direction variability, R degrees.

(7) Wind speed, knots.

The calculation method assumes that all input parameters are horizontally homogeneous. This is a particularly good assumption when the agent is sprayed onto a fire. A sample calculation is shown below.

The diffusion factor of a chemical depends on the environment. One important parameter is the solar elevation angle, E (the angle of the line of sight of the sun with a horizontal plane), which is determined from the solar angle of incidence I (the angle between the beam radiation on a horizontal surface and the normal to that surface) by the relationship

$$E = 90 - I \qquad (27)$$

The angle of incidence can be determined (Reference 46)

$$\cos I = \cos S \cos L \cos W + \sin S \sin L \qquad (28)$$

Here S is the solar declination angle, L is the latitude, and W is the hour angle (the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15 degrees per hour). The solar declination angle is determined by

$$S = 23.45 \sin \frac{360 \ (284 + n)}{365} \qquad (29)$$

where n is the day of the year. For November 15, n = 319 and S = -19.15 degrees. For Albuquerque, New Mexico, L is 35.05 degrees and W, for 10 a.m. is -30 degrees. Using these values in Equation (28) and taking the inverse cosine gives I = 61.225 degrees. From Equation (27), E is 28.8 degrees.

The toxic corridor length (TCL) is a product of the diffusion factor (DF) and the chemical factor (CF) where the diffusion factor is given by

$$DF = Q^{0.513}(\Delta T + 10)^{2.53} \qquad (30)$$

and the chemical factor, by

$$CF = 30.476 \ (CP \times GMW)^{-0.513} \tag{31}$$

The source strength, Q, is assumed to be the nozzle discharge rate for 1 minute. For the 2.5 kg/s (5.5 lb/s) discharge, Q is 330 lb/min. Since there is a very high heat from the fire, and since the Halon 2402 is released from a nozzle which causes droplet formation, the halon is expected to evaporate immediately. Thus, taking the source strength as the discharge rate is a valid assumption.

An approximate value of ΔT can be determined from Table B-1 in Reference 45. This table requires knowledge of the solar elevation angle (28.8 degrees), cloud condition (broken clouds at and below 2134 meters, 7000 feet, were assumed), and the surface wind (8 km/h, 5 mi/h, was assumed). Table B-1, Reference 45, gives a ΔT of 0 degrees. From Equation (30), DF = 6637.

The chemical factor is a function of the exposure limit, CP, and the GMW of the toxic chemical. For Halon 2402, GMW = 259.83 and CP is taken as 1000 ppm. From Equation (31), CF = 0.0766.

The product of the values of CF and DF give the TCL as 155 meters (508 feet). Use of the dispersion program described earlier gives a TCL of approximately 100 meters if the stability category is D and somewhat less if the stability category is C. With a wind speed between 6.44 and 16.1 km/h (4-10 mi/h) and wind fluctuation information unavailable, the wind variability factor, R, is taken as 60 degrees. The width, W, of the toxic corridor is then determined from

$$W = 1.5R \tag{32}$$

In the present example, W is 90 degrees.

Table 48 presents toxic corridor parameters for Halon 2402 for source strengths of 150 kg/min (5.5 lb/s) and 259 kg/min (9.5 lb/s) for a variety of assumed toxic levels (CP). All calculated values are for weather conditions as described above. The corridor width can be taken as 90 degrees in each case. Note that these toxic corridors are concentrations along a plume centerline; therefore, they give some of the same information as obtained in the computer program "PLUME." In the present case, however, distance as a function of concentration (CP) is determined, rather than the converse.

The data indicate that for tests of the type described, personnel downwind from the test site would have to remain at a distance of 136 meters (446 feet) in the higher volume test to avoid concentrations above the maximum allowable under the U.S. Military recommended levels (1000 ppm). Of course, upwind personnel could be much closer.

Halon 2402 toxicity in a test of the type described here may cause less of a problem than the decomposition products, owing to the (unrealistically?) small concentrations allowed for inorganic halogen-containing materials. Toxic corridors have been calculated for bromine, fluorine, hydrogen bromide, and hydrogen fluoride produced in these tests, assuming decompositions of 1, 5, and 10 percent. The source strengths were determined from the stoichiometry of the decomposition. The toxic levels picked were those given in Table 33. The results are given in Table 49.

The results (excluding Sample 3, which was known to be contaminated with AFFF agent), as shown in Table 50, indicate that the purities of commercially produced Halon 2402 are greater than 99.7 percent (average, excluding Sample 3, 99.829 percent). Although the agent is advertised as 99.9 percent pure, the agent for firefighting purposes is sold as 99.5 percent pure by weight (Reference 4).

The limits presented in Table 33 are unrealistically low for fire scenarios, where the largest threat is probably not agent decomposition product toxicity. Nevertheless, using those limits, large corridors, up to approximately 0.8 km (1/2 mile) may be required depending on the percent decomposition. For long-lived fires, the decomposition might be several percent. Rapid extinguishment will give very little decomposition.

TABLE 48. TOXIC CORRIDORS FOR HALON 2402.

Source strength, lb/min	CP, ppm by volume	CF	DF	TCL, ft
330	450	0.0766	6637	508
330	550	0.0691	6637	459
330	650	0.0634	6637	421
330	750	0.0589	6637	391
330	850	0.0553	6637	367
330	1000	0.0508	6637	337
330	1250	0.0453	6637	301
330	1500	0.0413	6637	274
330	1750	0.0382	6637	254
330	2000	0.0356	6637	236
330	2250	0.0335	6637	222
330	2500	0.0318	6637	211
570	450	0.0766	8785	673
570	550	0.0691	8785	607
570	650	0.0634	8785	557
570	750	0.0589	8785	517
570	850	0.0553	8785	486
570	1000	0.0508	8785	446
570	1250	0.0453	8785	398
570	1500	0.0413	8785	363
570	1750	0.0382	8785	336
570	2000	0.0356	8785	313
570	2250	0.0335	8785	294
570	2500	0.0318	8785	279

TABLE 49. TOXIC CORRIDORS FOR HALON 2402 DECOMPOSITION PRODUCTS.

Material	CP,ppm	1% Decomposition		5% Decomposition		10% Decomposition	
		Q,lb/min	TCL,ft	Q,lb/min	TCL,ft	Q,lb/min	TCL,ft
5.5 lb/s nozzle discharge rate							
Br_2	0.3	2.0	2042	10.1	4656	20.3	6652
F_2	2	0.5	768	2.4	1755	4.8	2504
HBr	3	2.1	893	10.3	2039	20.6	2910
HF	3	0.5	895	2.6	2043	5.1	2915
9.5 lb/s nozzle discharge rate							
Br_2	0.3	3.5	2700				
F_2	2	0.8	1017				
HBr	3	3.6	1190				
HF	3	0.9	1182				

TABLE 50. HALON 2402 GC PEAK AREAS AS PERCENTAGES OF TOTAL AREA.

Aliquot	Sample number					
	1	2	3	4	5	6
1	99.835	99.753	97.938	99.797	99.824	99.844
2	99.858	99.746	98.002	99.827	99.888	99.902
3	99.873	99.721	99.286	99.827	99.851	99.891
Average	99.855	99.740	98.075	99.817	99.854	99.875
Deviation[a]	0.014	0.013	0.140	0.013	0.022	0.010

[a]Average deviation.

4. Conclusions

a. General air dispersion and toxic corridor calculations both give reasonable results when applied to releases of Halon 2402 and its combustion products. Owing to the very small levels permitted for inhalation of inorganic decomposition products, such calculations can give very long toxic corridors for pyrolysis products.

b. A generalized BASIC computer program ("PLUME") to calculate concentrations originating from a release is available in this report.

c. At distances of 100 meters and beyond, the spill of a 208-liter (55-gallon) barrel of Halon 2402 is unlikely to give concentrations which are immediately dangerous.

d. The concentrations encountered for a given source rate are much larger at night and with overcast skies; however, under these conditions, the evaporation rate is probably smaller. An exception occurs with extinguishment operations at night, where the evaporation rate would be high.

e. With a 4.3 kg/s (9.5 lb/s) nozzle discharge, personnel downwind must maintain a distance of approximately 152 meters (500 feet) to keep below the U.S. Military recommended maximum allowable Halon 2402 concentration.

f. Halon 2402 dispersion depends strongly on climatic conditions and less strongly on wind velocities.

F. STRATIFICATION

1. Objectives

A given volume of gaseous Halon 2402 (GMW = 259.83) is over 50 percent heavier than the same volume of either Halon 1301 (GMW = 148.9) or Halon 1211 (GMW = 165.4). This difference in gas density increases the stratification of Halon 2402 following application. Stratification is also induced for all halons due to cooling by the latent heat of vaporization. In this section, Halon 2402 stratification tendencies are examined.

2. Smokehouse Test

The "smokehouse" concrete-block structure used for fire testing at Kirt-
land AFB was modified with plywood partitions to give a cubic room, 3 meters
(10 feet) on a side. A fire extinguisher containing 2.3 kg (5 pounds) of Halon
2402 was mounted at the ceiling and was discharged downwards in 2 to 3 seconds.
Ten grab samples were taken with evacuated bottles at various times following
the discharge. The ambient temperature and pressure for the test were
approximately 65 °F and 630 Torr.

The concentrations were determined by infrared (IR) spectroscopy.
Calibration was achieved by determining the intensity of an IR spectral peak as
a function of absolute pressure for a pure sample of Halon 2402. A total of 23
points were taken for the calibration between 1 and 35 Torr. The IR peak area
of the sample determines the partial pressure of the Halon 2402, and the ratio
of that partial pressure to the total pressure gives the volume fraction. The
results are shown in Table 51.

3. Discussion

The stratification during this test caused the concentrations at the
1.52-meter (5-foot) level to range from 25 to 52 percent of those at the floor
for samples taken at the same time. Percentages determined in this way are
termed "stratification values" in the remainder of this report. A small
stratification value indicates a large amount of stratification. Initially,
the stratification in the center of the room was less than that at the wall
(stratification values of 52 percent at the room center and 35 percent at the
wall). After 3 minutes this ordering reversed as Halon 2402 appeared to settle
rapidly at the room center (after 3 minutes, 25 percent at the room center and
33 percent at the wall). The stratification appeared to be most constant at
the wall. Air currents set up by temperature changes due to Halon 2402
evaporation and by the discharge itself may have greatly influenced the differ-
ences between the room center and the wall.

Large stratifications were also observed in the enclosed fire
extinguishment tests (Table 41). In these tests, the stratification was
relatively constant over time. The pan fire was apparently too small to cause
good agent dispersion through buoyancy effects.

TABLE 51. SMOKEHOUSE STRATIFICATION TEST.

Grab sample location[a]	Height from floor, m	Sampling time after discharge, min:s[b]	Concentration, ppm
Wall	1.52	0:20	7,175
Center	1.52	0:20	8,725
Wall	0	0:20	20,225
Center	0	0:20	16,750
Wall	1.52	1:30	5,950
Center	0	1:30	18,675
Wall	1.52	3:00	5,950
Center	1.52	3:00	4,400
Wall	0	3:00	18,050
Center	0	3:00	17,425

[a]The bottles were located either half way along a wall or in the room center. No samples were taken at the room corners.

[b]This is the time following the start of the discharge.

Large stratifications were also observed in the enclosed fire extinguishment tests (Table 41). In these tests, the stratification was relatively constant over time. The pan fire was apparently too small to cause good agent dispersion through buoyancy effects.

Experiments at the University of Milan (Reference 47) have determined the distribution of Halon 2402 concentrations in a room with a volume of 24.44 m^3 (863 ft^3) following discharge of 6.85 kg (15.1 pounds). Samples were taken at six different points in the room at three heights and three times.

Unfortunately, the results are not readily comparable to those obtained in the smokehouse test since the University of Milan test used a side discharge and a 28 cm (11-inch), 1250 rpm fan to circulate gas during the test. The University of Milan test showed relatively good distribution of concentrations between points at the same level and time; however, even with a fan, the average stratification values between 60 and 180 centimeters (approximately 2 and 6 feet) were 29, 81, and 86 percent after, respectively, 30, 60, and 120 seconds.

Tests of the fire protection system in hardened aircraft shelters (Reference 48) have shown that stratification also occurs with Halon 1211 (Reference 48). These tests also show that agent dispersion is increased in the presence of fires due to buoyancy effects and that the magnitude of this dispersion appears to be a direct function of fire size.

Stratification of Halon 2402 inorganic decomposition products will be the same as that of the inorganic decomposition products of other halons containing only bromine, fluorine, and carbon (e.g., Halon 1301). The large molecular weight of Halon 2402 will have no effect on pyrolysis product stratification.

4. Conclusions

a. The large molecular weight of Halon 2402 and the temperature drop on discharge can cause serious stratification in enclosed areas. Concentration variations of 4:1 (stratification values of 25 percent) may not be unreasonable over a 1.52-meter (5-foot) vertical distance.

b. Stratification is not unique to Halon 2402. A similar effect is seen with Halon 1211.

c. Agent dispersal and decreased stratification will be induced by the presence of a fire and will increase with increasing fire size and temperature.

d. Though artificial circulation of air can decrease stratification, significant concentration variations can still occur.

G. ENVIRONMENTAL ASSESSMENT

1. Objectives

The following presents an overview of the legal (Reference 49) and
environmental impact aspects of discharges of Halon 2402. The following sub-
jects are considered: transportation, hazardous waste, toxic substances, water
quality, and air quality including stratospheric considerations.

2. Survey

a. Transportation

The transportation of hazardous materials is covered by the
regulations of the Federal Department of Transportation in Title 49 - Transpor-
tation, Code of Federal Regulations. Of particular importance to shippers and
receivers are Parts 102 and 107, which outline procedural guidelines for the
Materials Transportation Bureau, and Parts 171 through 179 and Part 397, which
prescribe rules for shippers, transporters, and manufacturers (Reference 50).

Shippers must determine whether materials being offered for
transportation have the characteristics of one or more of the hazardous materi-
als defined in the "Hazardous Materials Regulations" of the U.S. Department of
Transportation. The shipper is assisted by the Hazardous Materials Table
(49 CFR 172.101) which lists, in alphabetical order, materials considered to be
hazardous. Halon 2402 is not included on this list. Halon 1301 (listed by its
chemical name, bromotrifluoromethane) is included, owing to its requirement of
a pressurized container. A material may not appear on this list and yet be a
controlled substance. Controlled materials fall into the categories of explo-
sives, compressed peroxides, oxidizing materials, poisons, irritating materi-
als, corrosives, etiologic agents, radioactive materials, and other regulated
materials. Only the categories of poisons and other regulated materials could
be of importance in considerations of Halon 2402 transportation.

The regulations define two types of poisons - Class A (highly
toxic) and Class B. Halon 2402 cannot be considered a highly toxic material.

Only the Class B characteristics need be considered. Class B materials have minimum oral LD_{50} values of 50 mg/kg, minimum inhalation LC_{50} values of 2 mg/L (equal to < 1 ppm for Halon 2402) for a 48-hour exposure, and minimum skin absorption LD_{50} values of 200 mg/kg for a 24-hour exposure. All values are based on rat studies. The toxicity of Halon 2402 falls outside of these ranges in all cases. There is, however, a final characteristic of a Class B poison. A material known be experience to cause serious sickness or death is considered a Class A poison. Since Halon 2402 is known to have caused human fatality,* it might be considered a Class B poison even though large concentrations are required for human toxicity. This is a matter which must be determined by legal authorities.

An Other Regulated Material (ORM) is a material that "(1) may pose an unreasonable risk to health and safety or property when transported in commerce; and (2) does not meet any of the definitions of the other hazard classes" (49 CFR 173.500). Included in the characteristics of an ORM is "A material which has an anaesthetic, irritating, noxious, toxic, or other similar property and which can cause extreme annoyance or discomfort to passengers and crew in the event of leakage during transportation." Since Halon 2402 has anaesthetic properties, it may well be declared an ORM even if it is not considered a Class B poison.

b. Hazardous Waste

The proper disposal of waste Halon 2402 is of concern in its utilization. The regulations concerning the classification of wastes are complex and open to differing interpretations.

The Resource Conservation and Recovery Act (RCRA) of 1976 (Public Law 94-580) as amended mandates hazardous waste management. Section 3001 of Subtitle C, Hazardous Waste Management, calls for the developement of criteria for the identification and listing of hazardous waste. Part 261 of Title 40 of the Code of Federal Regulations (CRF) carries out this requirement.

---

* Gloria, C. M., **Report on the Experiments Concerning Human Exposure to Fluorene Carried Out on July 13, 1970**, a memo addressed to Dr. A. Ferri, University of Milan, July 14, 1970.

If a material is to be classified as a hazardous waste, it must not be recycled, used as a fuel, or be employed in some other useful function; otherwise, it will not be classified as a hazardous waste, regardless of its characteristics (though it could still be a hazardous material and subject to DOT, OSHA, TSCA and other regulations).

There are two types of criteria for hazardous waste under RCRA. First, Subpart C of 40 CFR 261 lists four characteristics to be used to determine if a waste is hazardous: ignitability, corrosivity, reactivity, and EP toxicity. If a waste meets at least one of these criteria, and is not excluded from regulation, it is classifiable as hazardous. Second, Subpart D contains lists of materials declared to be hazardous waste. If a waste appears on one of these lists, then it is defined as hazardous. These subparts are reviewed below in an abridged outline of the regulations.

Subpart C: Characteristics, Ignitability (40 CFR 261.21)--A waste exhibits the characteristics of ignitability if it

1. is a liquid, other than an aqueous solution containing less than 24 percent alcohol and has a flash point less than 60 °C (150 °F),

2. is not a liquid and can cause fire through friction, absorption of moisture, or spontaneous chemical changes, and, when ignited, burns so vigorously that it creates a hazard,

3. is an ignitable compressed gas,

4. is an oxidizer.

Subpart C: Characteristics, Corrosivity (40 CFR 261.22)--A waste exhibits the characteristics of corrosivity if it

1. is aqueous and has a pH of 2 to 12.5,

2. is a liquid and corrodes steel at a rate greater than 6.35 mm per year at 55 °C.

211

Subpart C: Characteristics, Reactivity (40 CFR 261.23)--A waste
exhibits the characteristic of reactivity if it

1. is normally unstable and readily undergoes violent change,
2. reacts violently with water,
3. forms explosive mixtures with water,
4. generates toxic gases in water,
5. is a cyanide or sulfide giving toxic gases at pH 2 - 12.5.
6. is capable of detonation or is a defined explosive.

Subpart C: Characteristics, EP Toxicity (40 CFR 61.24)--A waste
exhibits the characteristics of EP toxicity if the extract, obtained as
described in the Extraction Procedure (EP) (Reference 51), contains metal or
metalloid concentrations equal to or greater than the concentrations shown
below

As	5.0 mg/L	Pb	5.0 mg/L
Ba	100.0 mg/L	Hg	0.2 mg/L
Cd	1.0 mg/L	Se	1.0 mg/L
Cr	5.0 mg/L	Ag	5.0 mg/L

or if it contains the pesticides Endrin, Lindane, Methoxychlor, or Toxaphene,
or the herbicides 2,4-D or 2,4,5-TP Silvex at prescribed concentration levels.

Subpart D: Listed Wastes--Subpart D of 40 CFR 261 contains
lists of wastes which have been declared hazardous. Section 261.31 lists
hazardous wastes from nonspecific sources (the F-list). Section 261.32 list
wastes from specific sources (the K list). Discarded commercial chemical
products, off-specification species, container residues, and spill residues are
contained in the P-list of acute hazardous wastes and the U-list of toxic
wastes in Section 261.33.

Appendix VIII, 40 CFR 261, Hazardous Constituents--This appendix
presents an interpretive problem. A careful reading of 40 CFR 261 shows that
this list is meant to be a guide in determining which materials should be

listed. Appendix VIII is not meant to have independent regulatory status.
This is the interpretation of many environmental authorities and lawyers
(Reference 52). Note, however, that this interpretation is apparently not
universal. One published paper states, that "Appendix VIII was originally
accepted by the regulated community as having no independent regulatory status.
The Agency is assuming, however, that it indeed has full regulatory status..."
(Reference 53). This article was not written by any member of a regulatory
agency.

    c.   Discussion

       Halon 2402 possesses none of the "Characteristics of Hazardous
Waste," nor is it a listed waste. Nevertheless, there are some problems with
disposal. First, the following section is present within the RCRA itself
(Public Law 94-580), Section 104:

> (5) The term "hazardous waste" means a solid waste or
> combination of solid wastes, which because of its
> quantity, concentration, or physical, chemical, or
> infectious characteristics may --
>   (A) cause, or significantly contribute to an
>   increase in mortality or an increase in serious
>   irreversible, or incapacitating reversib.e,
>   illness; or
>   (B) pose a substantial present or potential hazard
>   to human health or the environment when improperly
>   treated, stored, transported, or disposed of, or
>   otherwise managed.

       Halon 2402 may very well meet this criterion for a hazardous
waste. Disposal of large amounts of liquid Halon 2402 could be considered a
threat to human health in case of container leakage or rupture. A second
problem with disposal of Halon 2402 is its physical state. In general, whether
considered hazardous or not, liquid wastes are no longer acceptable for
landfill disposal.

d. Toxic Substances

A good overview of the general hazards of Halon 2402 is found in Reference 54. There are two acts of importance in considering the toxicity of Halon 2402. The first is the Toxic Substances Control Act (TSCA), which calls for regulation of the production, use, distribution, and disposal of hazardous materials (Reference 55). Since TSCA primarily concerns manufacturers and shippers and many of the regulations are covered elsewhere, this need not be discussed here.

The second is the Occupational Safety and Health Act, administered by the U.S. Occupational Safety and Health Administration (OSHA, Reference 56). This act was written to assure that "no employee will suffer material impairment of health or functional capacity" from a lifetime of occupational exposure." Federal and state employees are presently excluded from this act; nevertheless, the Federal Government has attempted to meet the spirit of the act. In 1980, a new Presidential Executive Order was issued, which broadened the responsibility of federal agencies for protecting their workers. Lists of toxic and hazardous substances are contained in 29 CFR 1910. At present, Halon 2402 is not contained in this list. It is possible, however, that this material and other halons will some day be added. When and if that occurs, monitoring programs would be necessary for nongovernmental agencies to assure compliance with standards.

c. Water Quality

In 1972, Congress established the basic structure for water quality control with its enactment of the Federal Water Pollution Control Act. In 1977, the act was extensively modified and became the Clean Water Act. Among the regulations which have come from this act are several lists of chemicals whose discharge is regulated and whose concentrations are monitored. The basic list, the Priority Pollutants list of 129 materials, has been extended by three other lists - The Consent Decree Appendix C Pollutants, the Consent Decree Paragraph 4(c) Pollutants, and the Synthetic Fuels Pollutants. An excellent summary of the history of these lists and their present structure (materials are constantly being added to or deleted from these lists) is contained in Reference 57. Halon 2402 is contained on none of these lists;

however, some closely related materials, including dibromodifluoromethane, are. It is extremely unlikely that Halon 2402 will be added to the Consent Decree lists in view of its low toxicity and the absence of chlorine in the compound. Much of the concern of the EOA is with chlorinated materials. It is much more likely that Halon 1211 will someday be added because of its chlorine content.

f. Air Quality

The Clean Air Act of 1970, as amended, establishes a Federal mandate to establish appropriate regulations to prevent air pollution. In general, the regulations concern air quality rather than emission standards. At present only a few National Emission Standards for Hazardous Air Pollutants (NESHAP) have been issued, and only two of these have been for organics (vinyl chloride, benzene). A few more organic materials are under consideration but none of these are halons.

Of considerable concern has been the effect of halogenated hydrocarbons, in particular the Freons, on the stratospheric ozone depletion (Reference 58). The effect is due to the chlorine cycle, which causes eventual removal of ozone (Reference 59). Although Halon 2402 contains no chlorine, recent results indicate that halons have a severe effect on stratospheric ozone, apparently due to the other halongens. It has been stated that ozone degradation by Halon 1301 (which should be similar to Halon 2402 on its effect on ozone) is 10 times more severe than that by Freon 12.*

4. Conclusions

a. Halon 2402 may someday be condidered as a Class B poison or as an ORM in transportation regulation. This would require special placarding and packaging when shipped from the manufacturer, when transported after delivery, and when wastes are transported for disposal. At present, Halon 2402 is not being shipped as a hazardous material by manufacturers.

---

* Stephen Anderson, Environmental Protection Agency, Washington D.C., private communication.

215

b.   Though disposal of Halon 2402 is not specifically regulated under RCRA, it should be treated as a hazardous waste to meet the spirit of the act. It cannot be landfilled even as a nonhazardous waste. Incineration is an acceptable disposal method.

c.   Contamination of water supplies should be avoided. There is no specific regulation covering Halon 2402 at present; however, it is possible that future regulations will cover classes of materials which would include this agent. It is, however, unlikely that 2402 will be listed specifically as a regulated polluter in the foreseeable future.

d.   If and when OSHA regulates the use of Halon 2402, personnel monitoring systems will have to be established and concentrations will have to be checked. The use of dispersion and evaporation information contained in this report may help in preventing excessive exposure.

e.   The impact of Halon 2402 and other halons on the air and stratosphere could be significant. There is a strong probability that releases of halons may be regulated at some future date.

SECTION V

MILITARY SPECIFICATION TESTING

In this section, the testing and considerations necessary to develop a specification for Halon 2402 are presented. Gas chromatography data related to this section are contained in Appendices H and I (Volume II). The proposed draft Military Specification is contained in Appendix J (Volume II).

A. PURITY ANALYSIS

The mount of impurities and the variability of selected samples of Halon 2402 were determined by gas chromatography (GC) and gas chromatography/mass spectrometry (GC/MS). The flame ionization detector response is roughly proportional to the moles of carbon present. Thus, a comparison of the area of the GC peak of Halon 2402 to the total area of all peaks gives an estimate of the total amount of contaminants. If the molecular weights of all components present are proportional to the numbers of carbon atoms in the molecules (a rough approximation for similar compounds), then the areas of the GC peaks expressed as percentages of the total area give the weight percentages of the components.

1. Experimental

a. Gas Chromatography

Six samples of Halon 2402 were tested. Samples 1 and 2 were taken from drums of Montedison Fluobrene shipped from New York, New York, and Samples 3-5 were collected from drums of Fluobrene shipped from Houston, Texas. Sample 6 was obtained from Great Lakes Chemical Corporation, West Lafayette, Indiana 47906. The Montedison product is produced in Italy while the Great Lakes material is produced in Japan. Sample 3 was contaminated during field testing with AFFF, and the test data from this sample must be viewed with suspicion.

In the initial GC analyses, the samples were chromatographed on the HP 5880A GC at a constant temperature of 30 °C. The following parameters were used: column pressure, 15 lb/in.^{2}; septum purge vent flow rate, 2 mL/min;

split vent flow rate, 53 mL/min; split ratio, 50:1; hydrogen flow rate to the detector, 30 mL/min; airflow rate to the detector, 240 mL/min; injection, split; chart speed, 1 in/min; attenuation, 3. Under these conditions, with this instrument, only one impurity peak was observed for Samples 1-5 and none for Sample 6. The injection sizes, retention times, and areas expressed as percentages of the total area are shown in Table H-1, Appendix H (Volume II). The retention times exhibit a distinct sample quantity dependence, increasing with increasing injection size. The chromatograph of Sample 1 is shown in Figure H-1, Appendix H.

To obtain additional purity data, the samples were chromatographed again on the HP 5890 GC using a higher detector gain and employing a temperature program. Three 2 µL aliquots of each sample were analyzed. The injection temperature was 200 °C and the flame ionization detector (FID) temperature was 250 °C. For Samples 1-5, the column temperature was programmed to hold 30 °C for 3 minutes, ramp at 20 °C to 150 °C, and hold at 150 °C for 2 minutes. For Sample 6, the initial temperature was 35 °C rather than 30 °C. The helium column flow rate was 1 mL/min, increased to 30 mL/min with makeup gas. The hydrogen and airflow rates to the FID were 30 mL/min and 450 mL/min, respectively. A septum purge of 4 mL/min and a split vent of 100 mL/min (split ratio, 100:1) were employed. The chromatograms of Samples 1 and 6 (Montedison and Great Lakes Chemical Corporation products) are shown in Figures 62 and 63. The chromatograms of the remaining samples are contained in Appendix H. The retention times and peak areas for reproducible peaks are presented in Table H-2. The peak area of the Halon 2402, as compared to the sum of all peak areas, is presented in Table 50.

b. Gas Chromatography/Mass Spectrometry

The six samples were also analyzed by gas chromatography/mass spectrometry (GC/MS). The samples were run isothermal at room temperature (except for Sample 6 which was ramped to 150 °C to bring off some peaks with large retention times). The column pressure was 18 lb/in.^{2} with a split ratio of 20:1 and the injection size was 3 µL. A total ion current chromatogram for Sample 1, similar to those for Samples 2-5, is shown in Figure 64. The GC/MS of Sample 6 is discussed later. Six peaks were observed and identified (in some cases, tentatively). The peak with the lowest retention time was due to
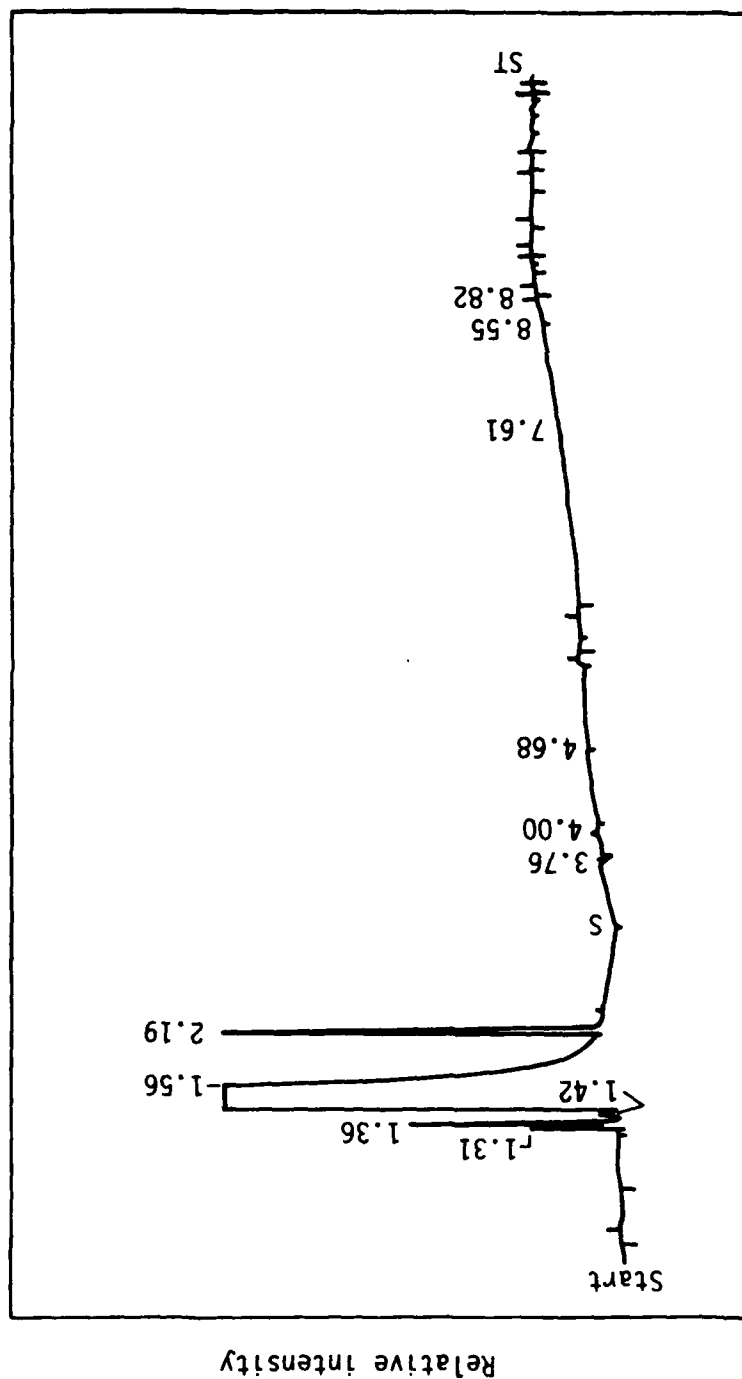
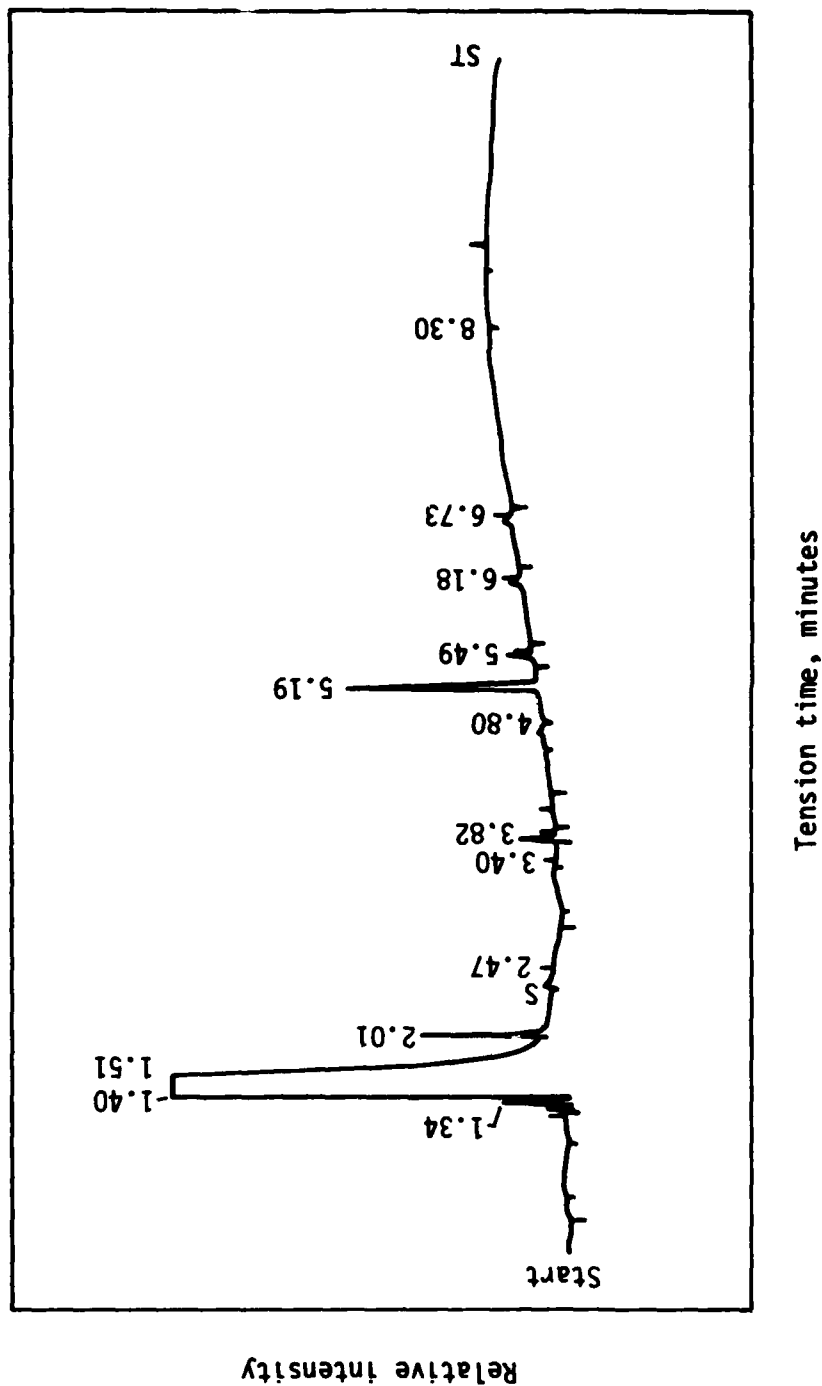Figure 62. Chromatogram of Sample 1 from HP 5890A Gas Chromatograph.

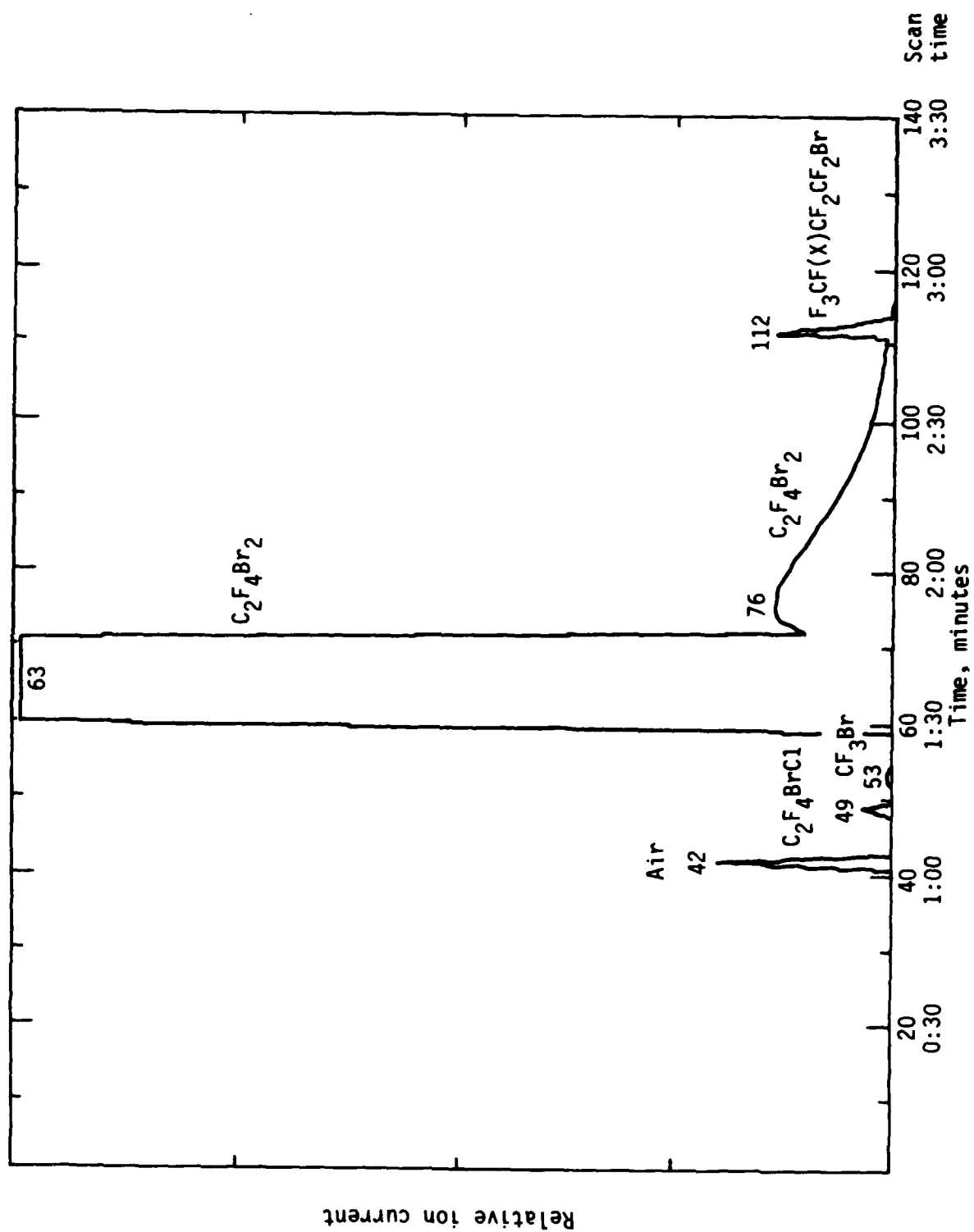Figure 63.   Chromatogram of Sample 6 from HP 5890A Gas Chromatograph.

Figure 64. Total Ion Current Chromatogram of Sample 1 by GC/MS.

221

air as determined from the mass spectrum, not shown, which exhibited only N_2^+, O_2^+, and Ar^+ major mass peaks and minor peaks caused by CO_2 and H_2O and their fragments. The large chromatographic peak caused by Halon 2402 was split owing to injection overload. The mass spectra of the various components are presented and discussed in Appendix I.

The GC/MS results for Sample 6 are somewhat different from those obtained for Samples 1-5. The total ion chromatogram is shown in Figure 65 and the assignment of peaks is discussed in Appendix I.

2. Discussion

Inspection of the chromatograms in Figures 62-63, Figures H-2 through H-5, and Table H-2 shows that there are some purity differences between Halon 2402 samples. Thus while Samples 1-5, all from Montedison, resemble each other in contaminants (excluding Sample 3, which was known to be contaminated after it left the manufacturer), there are differences in amounts of contaminants. Thus, Sample 2 exhibits gas chromatographs indicative of a large number of impurities, particularly at the higher molecular weights. The single sample (Sample 6) from Great Lakes Chemical Corporation differs to a marked degree from those from Montedison. The differences are most pronounced when considering the components identified in the GC/MS work. Identified from Samples 1-5 were 1-bromo-2-chlorotetrafluoroethane (CF_2BrCF_2Cl), bromotrifluoromethane (CF_3Br), and a fluorinated bromobutane ($F_3CFXCF_2CF_2Br$, X not identified). On the other hand, in Sample 6, the identified impurites are dibromodifluoromethane (CBr_2F_2), dibromochloromethane ($CHBr_2Cl$), tribromomethane ($CHBr_3$), a dibromochloro compound ($RCBr_2Cl$), and a high molecular weight brominated aliphatic amine ($RBrNH_2$). The latter material may interfere with the water analysis (see below). Among the components which have previously been identified in Halon 2402 are those shown in Table 52.
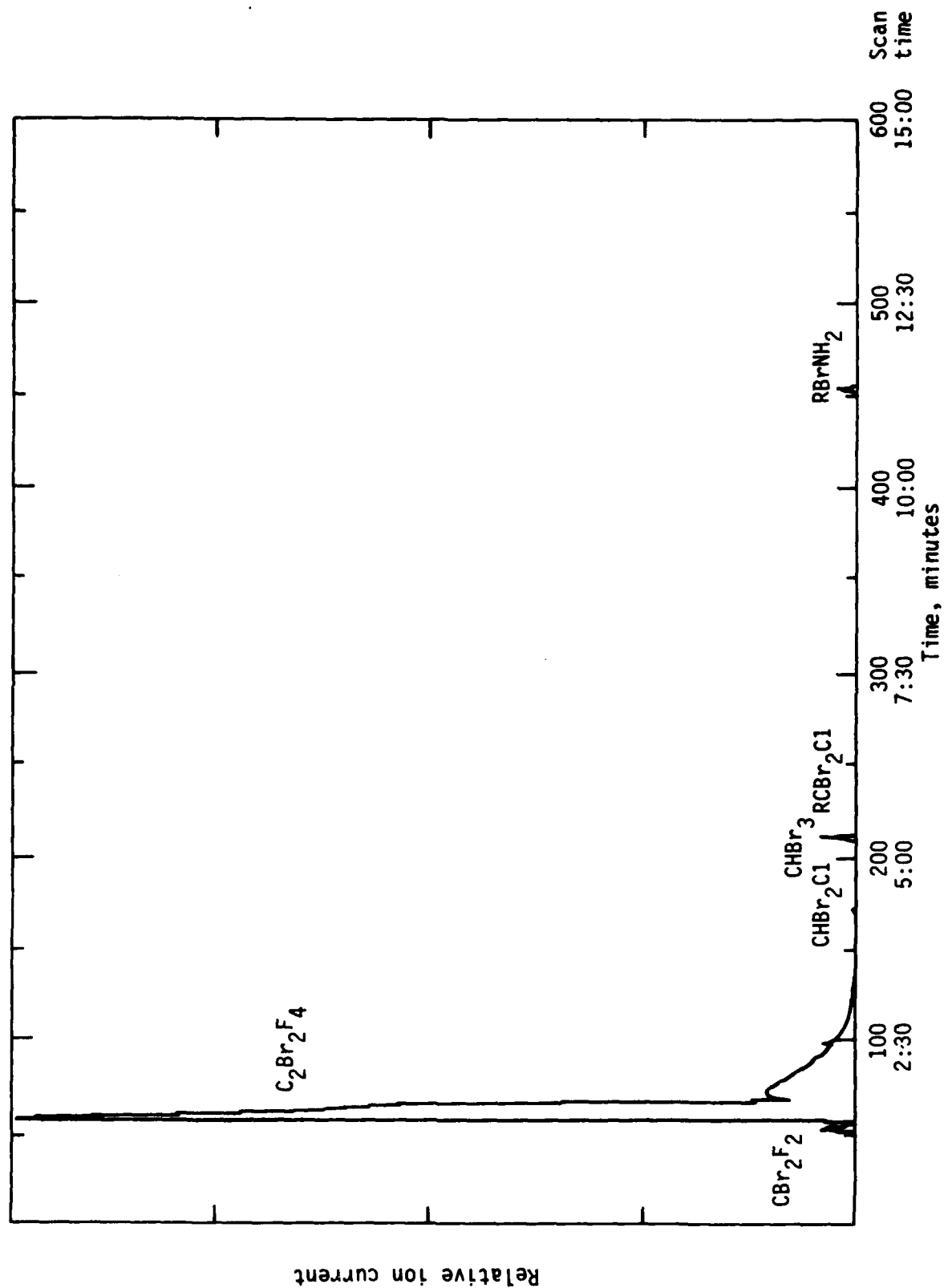
Figure 65. Total Ion Current Chromatogram of Sample 6 by GC/MS.

223

TABLE 52. IMPURITIES IN HALON 2402.[a]

Compound	Concentration
CHF_3	3-5 ppm
CH_2Cl	0.01 percent by weight
$CBrF_2CClF_2$[b]	0.01-0.04 percent by weight
CBr_2F_2	0.03-0.04 percent by weight
$CBrF_2CF_2CBrF_2$[c]	0.04 percent by weight

[a]Reference 54.

[b]Also observed in the present study.

[c]May have been observed in this study.

A number of other compounds have been observed upon aging Halon 2402, including CF_3Br, which was also found in the present study. Diisooctylphthalate has been found in some studies on Halon 2402.* Phthalates are used as plasticizing agents, and it is known that some of this phthalate was extracted from plastics or elastomers in contact with the Halon 2402 during transfer. Small amounts (1-4 ppm) of phthalates were also found in some freshly opened drums.

3. Conclusions

a. The purities determined here generally exceed 99.7 percent. The requirement of 99.6 percent purity for the miltary specification equals or exceeds that imposed on other halons (References 60, 61).

b. Contaminants in Halon 2402 vary from lot to lot and, in particular, between manufacturers.

c. Additional work is desirable to determine the hazards and agent use problems associated with impurities found in Halon 2402 and other halon agents.

---

* Humphrey, B. J., and Smith, B., **Toxicity of Halon 2402**, Air Force Engineering and Services Center, Tyndall Air Force Base, Florida, work in progress.

B. ACID HALIDE ANALYSIS

An analysis was conducted for the presence of acid halides in Halon 2402. Acid halides (HX, X = F, Cl, Br, I)) are formed upon decomposition of halons in the presence of water or other source of hydrogen ion. This decomposition occurs as a result of hydrolysis (reaction with water) and is accelerated by heat and light. The presence of excess acid halides increases the corrosivity of the agent to storage containers and equipment. In a fire, the decomposition of the halons to produce acid halides is, to a large extent, responsible for fire extinguishment; however, the presence of hydrogen halide in halons prior to use can cause severe problems with storage and handling of the agent.

1. Experimental

The acid halide content was determined following ASTM method D-2989--"Acidity Alkalinity of Halogenated Organic Solvents and Their Admixtures" (Procedure A, using a glass electrode pH meter). The pH meter used in these determinations was an Orion Research Model 611 pH meter with a Ross combination pH electrode. The only deviation from the stated procedure was the use of 25 ml (instead of 50 ml) of Halon 2402. The acid halide content was calculated as ppm (by weight) HBr according to the equation

$$\text{ppm acid halides} = \frac{V \times N \times 0.0809 \times 10^6}{\text{weight of sample (grams)}} \qquad (33)$$

where V is the volume in milliliters of NaOH solution required for titration of the sample and N is the normality of the NaOH solution (0.01 for this study).

The acid halide content was determined on four samples of Halon 2402: Samples 1, 3, 5, and 6. (The sample numbers correspond to the samples described in the portion of this section covering the purity analysis.) Two acid halide determinations were carried out on each sample. The results are summarized in Table 53.

TABLE 53. DETERMINATION OF ACID HALIDE IN HALON 2402.

Sample	Determination	Volume NaOH, ml	Concentration HBr, ppm
1	1	0.025	0.37
	2	0.025	0.374
3	1	0	0
	2	0	0
5	1	0.05	0.748
	2	0.05	0.748
6	1	5.60	83.8
	2	5.45	81.5

2. Discussion

The acid halide content determined for Samples 1, 3, and 5 is well within the specification limits stated by their manufacturer (Reference 4). The acid halide content determined for Sample 6 is out of specification; however, it is known that for some reason the sample sent for analysis by the distributor of that material underwent some decomposition prior to these measurements being taken. This was first noted as a color change from clear to yellow, the coloration being caused by the presence of excess free bromine. The amount of acid halide present in Sample 6 was sufficient to decrease the pH of the aqueous solutions on which the acid halide determination was accomplished from an average value of 6.98, for Samples 1, 3, and 5, to an average value of 2.92, for Sample 6. The amount of acid halide present in Sample 6 would undoubtedly cause problems with corrosion of containers or equipment. Although the exact cause of the decomposition of Sample 6 was unknown, it was felt that it was due to a combination of exposure of the sample to air and light (the sample was shipped in a clear glass container and should have been in a brown glass container).

Based on the information collected as a result of this study, the value proposed in the Draft Military Specification contained in Appendix J of 3.0 ppm maximum acid halide content is a good limit. This limit represents a valid decision point between material that is of acceptable quality and material which could present problems in storage and use.

3. Conclusions

a. The acid halide content of Halon 2402 which is of acceptable purity is in general less than 1 ppm by weight HBr.

b. The limit of 3 ppm by weight, maximum, acid halide content represents a valid decision point between material that is of acceptable quality and material that is of questionable quality. This limit meets or exceeds limits imposed on other halons (References 60, 61).

c. Care must be taken to ensure that samples collected for analysis are handled and stored properly prior to testing. Contact with heat and/or water must be avoided.

C. FREE HALOGEN ANALYSIS

The determination of free halogen was accomplished on several samples of Halon 2402 in order to assess the relevance of this requirement in the development of a Draft Military Specification for Halon 2402. Free halogen (X_2, where X is F, Cl, Br, or I) is formed upon decomposition of halon and may be present in small amounts as the result of manufacturing processes. For Halon 2402, the free halogen can only be bromine and fluorine (excluding the interhalogen compound BrF). The presence of free halogen increases the toxicity and corrosivity of the agent and may, therefore, cause problems with the storage and handling of the agent. In a fire, halon decomposes to form free halogens which are partially responsible for the fire extinguishment. Thus, decomposition under fire conditions is desirable.

1. Experimental

The amount of free halogen present was determined by liberation of iodine followed by titration with sodium thiosulfate solution according to the following procedure.

a. Reagents

(1) Sodium thiosulfate, 0.01 N solution: A 0.1 N solution was prepared by dissolving 25 grams of sodium thiosulfate ($Na_2S_2O_3 \cdot 5H_2O$) and 0.5 grams of sodium carbonate in 1 liter of distilled water. This was standardized against a 0.1 N potassium dichromate solution. A 0.01 N solution of sodium thiosulfate was prepared by pipeting a 10 mL aliquot of the standard 0.1 N solution into a 100 mL volumetric flask, filling it to the mark with distilled water, and mixing. The 0.01 N sodium thiosulfate solution was prepared fresh daily.

(2) Sulfuric Acid, 1:4 solution in water.

(3) Potassium iodide, 10 percent solution in water.

(4) Starch indicator.

b. Procedure

An aliquot of 100 mL of 10 percent potassium iodide solution was poured into a 250 mL Erlenmeyer flask and 10 mL of 1:4 sulfuric acid and 1 mL of starch solution was added. Dibromotetrafluoroethane vapor from evaporation of 100 grams of material was bubbled through the potassium iodide solution in a fume hood. Liberated iodine was titrated with the standard 0.01 N sodium thiosulfate solution. A reagent blank was run along with the sample.

c. Calculation

The mass fraction of free halogen, as bromine, was calculated as follows:

$$\text{ppm halogen (as } Br_2) = \frac{(A - B) \times N \ Na_2S_2O_3 \times 0.0799 \times 10^6}{\text{weight of sample in grams}} \quad (34)$$

where A is the volume of $Na_2S_2O_3$ used in titrating the sample, and B is the volume of $Na_2S_2O_3$ for the blank. Both volumes are in milliliters.

A determination of the free halogen content was carried out on Samples 1-6, which were described previously. An additional determination was accomplished on Sample 6 following the appearance of a yellow discoloration of the solution. For each sample, three experimental trials were conducted, the result averaged, and a standard deviation determined. The results of this study are contained in Table 54.

TABLE 54. FREE HALOGEN ANALYSIS OF HALON 2402.

Sample	Average bromine concentration, ppm	Standard deviation
1	10.66	0.231
2	11.99	1.38
3	8.39	3.86
4	9.45	4.74
5	6.53	3.05
6	13.55	1.84
6A[a]	46.8	6.8

[a]Sample 6 determination conducted after appearance of yellow coloration.

2. Discussion

The samples tested, with the exception of Sample 6A, contained less than 15 ppm free halogen, the average of the 6 determinations being 10.1 ppm. Sample 6A contained a large amount of free bromine relative to the other samples. This observation indicates that a significant amount of decomposition had taken place. The yellow coloration observed in Sample 6A is most likely due to the presence of excess free bromine. Literature from the manufacturer (Reference 4) contains no limits on the presence of free bromine in Halon 2402. The specified limits set on other halons in use by the military range from

3.0 ppm (Reference 61) to a qualitative test (Reference 60). Based on the above results, a proposed limit of 15 ppm by weight calculated as bromine represents a viable maximum allowable free halogen content. The proposed limit of 15 ppm is higher than the limit of 3 ppm specified for Halon 1211 (Reference 61); however, it is known that the stability of halons decrease with an increasing bromine content; therefore, a limit acceptable for Halon 1211 may not be realistic for other halons (e.g., the limit specified for Halon 1202 is 7 ppm by weight [Reference 62]). Additionally, the separation of free bromine at the manufacturing level is easier for the gaseous Halon 1211 than for the liquid Halon 2402 since bromine itself is a liquid.

A question must be considered before accepting the higher bromine limit for Halon 2402. Does the presence of an increased free halogen content affect the toxicity of the Halon 2402? To answer this question, a calculation was made of the bromine concentration in a 1000 ppm by volume mixture of Halon 2402 in air (the U.S. Military recommended maximum level for inhalation). The results of this calculation show that at a maximum free bromine content of 15 ppm in the Halon 2402, the bromine content of a 1000 ppm mixture of Halon 2402 in air would be 2.43×10^{-2} ppm by volume. This is well below the TLV/TWA for bromine of 0.1 ppm by volume (Reference 29). Therefore, the presence of 15 ppm free bromine in Halon 2402 does not significantly increase the toxicity of the agent.

3.   Conclusions

a.   The free halogen content of Halon 2402 averages approximately 10 ppm by weight calculated as free bromine.

b.   The limit of 15 ppm by weight (calculated as bromine) in the proposed Draft Military Specification (Appendix J) represents a realistic value on which to base decisions regarding the quality of the Halon 2402.

c.   The limit of 15 ppm by weight does not increase the toxicity of the Halon 2402, nor is it expected to present any special handling or storage problems.

D. ANALYSIS OF WATER CONTENT

An analysis was conducted for the moisture content in Halon 2402. The solubility of water in Halon 2402 at 25 °C is 80 ppm by weight. Above this value, a two-phase system exists with a water layer above the Halon 2402. The presence of water in halons causes formation of acid halides, which cause corrosion of storage containers and extinguishing equipment.

1. Experimental

The water content of Halon 2402 was determined by the Karl Fischer method in accordance with ASTM D-1744--"Water in Liquid Petroleum Products by Karl Fischer Reagent." The meter used in the determination of water content was an Orion Research Model 701A pH meter with a internal Karl Fischer circuit. The electrode used was an Orion Research double platinum electrode with standard taper. The Karl Fischer reagent was standardized against certified standard water in methanol. One determination was conducted on Samples 1, 3, and 5. Two determinations were also attempted for Sample 6; however, in both instances the reagent precipitated out. This phenomenon may have occurred due to the presence of decomposition products in this sample. The results of the analysis for water content in Halon 2402 are contained in Table 55.

TABLE 55. DETERMINATION OF WATER CONTENT IN HALON 2402.

Sample	Water content, ppm
1	26.5
3	70.2
5	27.8
6	--[a]

[a]Karl Fischer reagent precipitated during determination.

231

2. Discussion

The manufacturer's specification for water content in Halon 2402 is 15 ppm by weight (Reference 4). None of the samples tested were within the specified limit. It is possible that the samples were contaminated by atmospheric water as they were manipulated prior to testing. It is known that Sample 3 had been contaminated with AFFF while being pumped from the storage container to the sample container. As stated earlier, the determination of water content in Sample 6 was unsuccessful due to the degree to which the sample had decomposed.

In the development of specification limits for Halon 2402, factors such as handling, sampling, and manipulation of sample were taken into account in specifying a 20 ppm by weight maximum on the water content. This required maximum level is equal to that specified for Halon 1211 (Reference 61) and is higher than the 10 ppm specified for Halon 1301 (Reference 60). Halon 2402 is chemically less stable than Halon 1211 and therefore less tolerant of excess water content. The recommended test procedure, ASTM D-3401--"Water in Halogenated Organic Solvents and their Admixtures," is a widely used test method.

3. Conclusions

a. The maximum allowable water content of Halon 2402 should be specified as 20 ppm by weight. This represents a reasonable limit to ensure a quality product which is stable under storage and use conditions. The maximum allowable water content specified is slightly greater than the manufacturer's specification; however, this allows for some increase in water content as a result of sampling and handling, and does not affect the stability of the Halon.

b. Since Halon 2402 is somewhat less stable than other widely used halons (e.g., Halon 1211 and 1301), the water content must not be permitted to exceed the recommended limit.

E. ANALYSIS FOR NONVOLATILE RESIDUE

The amount of nonvolatile residue remaining after evaporation of a sample of Halon 2402 was determined for Samples 1-6. The presence of nonvolatile material gives an indication of halon purity. Such material could result from contamination, polymeric decomposition, the presence of additives, or deposits of metallic particles or pump oil during delivery operations. Although the presence of the impurities may not affect the performance of the agent, they affect cleanliness, which is one of the advantages of using a halon fire-extinguishing agent, and could create delivery or equipment wear problems. To ensure a high quality product, a limit is set on the presence of nonvolatile impurities.

1. Experimental

The amount of nonvolatile impurities was determined in accordance with Method B of ASTM D-2109--"Nonvolatile Matter in Halogenated Organic Solvents and their Admixtures." Five determinations were conducted on each sample with the exception of Sample 6, for which only three determinations were accomplished. The amount of nonvolatile residue was calculated and recorded as ppm of residue by weight. The results of these determinations were averaged for each sample and an average deviation was calculated. The results of this study are contained in Table 56.

TABLE 56. NONVOLATILE RESIDUE ANALYSIS FOR HALON 2402.

Sample	Nonvolatile residue, ppm	Average deviation, ppm
1	15	2
2	12	4
3	3	3
4	16	1
5	15	3
6	7	1

2. Discussion

One manufacturer's specifications designate a maximum nonvolatile residue of 50 ppm by weight (Reference 4). The specified limits for other halons in use by the military range from 88 ppm by weight for Halon 1202 (Reference 62) to 318 ppm by weight for Halon 1301 (Reference 60). All the samples tested were within the manufacturer's specified limits for nonvolatile residue.

Based on the results of this study, a limit on nonvolatile impurities of 50 ppm by weight is specified for Halon 2402 in the proposed Military Specification in Appendix J (Volume II). The method of analysis to be followed is Method A of ASTM D-2109, which is the preferred method of analysis for samples whose nonvolatile impurities are between 0 and 50 ppm by weight.

3. Conclusions

a. All samples tested were within the proposed maximum limit of 50 ppm by weight nonvolatile residue.

b. The analysis of nonvolatile residue in Halon 2402 represents a good quality check for purity of the agent. The proposed limit of 50 ppm maximum nonvolatile residue represents a realistic value on which to base decisions regarding the quality of Halon 2402.

SECTION VI
EQUIPMENT PARAMETERS

A. CYLINDERS

During this program, three different types of storage cylinders were used. Two systems were stainless steel and one was carbon steel. During the fire testing, a full description of each system was presented. The following is a summary description of each system.

The first system was a hand-held carbon steel extinguisher, which had an internal volume of 3.2 gallons. With 32 pounds of Halon 2402 and a 55 percent fill ratio, the cylinder was charged to an initial pressure of 200 lb/in.^{2}. The nozzles were made of aluminum and had straight-through orificed of various diameters and flow rates. This system was used in the medium-scale fire tests and the 28 ft^2 inertion tests.

The second system was a wheeled unit made of stainless steel. This cylinder will hold 10 gallons of agent at a 55 percent fill ratio. With a fixed pressure of 200 lb/in.^{2} and the rated fill ratio, the extinguisher will hold 180 pounds of Halon 2402. When using a constant flow system, up to 270 pounds of Halon 2402 can be stored in the extinguisher. During testing, this system used both the 1-inch and the 3/4-inch firehose. Most of the testing was done with 50 feet of 3/4-inch hose. Since this was a standard firefighting hose, a large array of nozzles could be easily adapted and tested. This system was used in the medium-scale cascading fires, the large-scale 3-D tests, the C-131 tests, and the 150 ft^2 pool fires.

The third system used was a P-13 firetruck. Initially the system was designed to carry 500 pounds of Halon 1211. For this project, one drum of Halon 2402 was used to charge the halon system. There were 200 kg (440 pounds) of agent in each drum. Theoretically, the system could be charged with 620 pounds of Halon 2402. The system was initially pressurized to 200 lb/in.^{2}. During the extinguishing run, the pressure dropped to 180 lb/in.^{2} in the tank, and the constant pressure system held it there. This system was used to suppress the 2200 ft^2 fires.

B. FIXED VERSUS CONSTANT CHARGE PRESSURE AND FILL RATIO

The cylinder fill ratio for Halon 2402 is dependent on how the system is charged. With a fixed initial charge, the maximum fill ratio is 55 percent. If a larger fill ratio is used, a large percentage of the agent will be below optimum pressure as it exits the nozzle. Previous testing has shown that the efficiency of Halon 2402 is greatly reduced when the nozzle pressure drops below 100 $lb/in.^2$.

There are two methods to increase the fill ratio. The first method is to use a higher fill ratio in a stronger tank with a proportionate increase in the overpressure gas charge. There is, however, a limit on the maximum charge. When the nozzle exit pressure is over 200 $lb/in.^2$, there is a reduction in agent efficiency. Thus, at higher pressures, the overall efficiency of the extinguishing system is reduced. The second method to increase fill ratios is by using a constant pressure system. With a constant pressure system, the cylinder is not pressurized and a fill ratio of up to 90 percent can be used. Instead, a high pressure bottle is used to pressurize the system. When the extinguishing system is needed, a valve is opened and regulated pressure from the high pressure bottle is used to charge the system and to maintain a fixed pressure while the agent is being discharged. With this system, the discharge pressure can be adjusted to any pressure and maintained there. With a fixed discharge pressure, there is no variation in the spray pattern and discharge rate. This allows the firefighter to confidently fight the fire without having to worry about a reduction in firefighting capability as the pressure in the storage cylinder drops.

To reemphasize, when using an extinguisher with a fixed charge of 200 $lb/in.^2$, the fill ratio should not be above 55 percent. A constant pressure system can be filled to 90 percent. However, it is the nozzle pressure which is important. Using the above specifications ensures the nozzle pressure will not drop below 100 $lb/in.^2$. If there is a lot of line loss with an individual system, the pressure may need to be increased to ensure the pressure at the nozzle does not drop below 100 $lb/in.^2$.

C. NOZZLE DESIGN

During the course of this project, a total of five types of nozzles were tested. Some of the types had several variations resulting in many actual nozzles. The types of nozzles were the following:

1. Firefighting water nozzles.
2. Water spray nozzles
3. Plain tip nozzles.
4. Penetrator tool.
5. Standard Air Force halon nozzles.

The design of the nozzle and the nozzle exit pressure control the flow rate of the agent. Knowing the exit pressure, which is controlled by the initial pressure and the line loss to the nozzle, is very important. Halon 2402 has twice the viscosity and a higher density than Halon 1211, resulting in increased line losses.

Factors which control line loss include the valving and hose diameters. Line losses are also dependent on the flow rate of the agent. With a fixed piping arrangement, the line losses increase logarithmically with increased agent flow. This became very important during testing on the large-scale fires. At an application rate of 9.0 lb/s in a 0.75-inch hose, the line losses are 85 lb/in.^{2}, an unacceptable value. In a 1.0-inch hose, the losses drop to 20 lb/in.^{2}, a value which is acceptable.

Testing has shown that the exit pressure is very important in determining the spray characteristics. With an exit pressure above 100 lb/in.^{2}, the spray angle changes very little. As the exit pressure increases, the droplet size decreases. At about 200 lb/in.^{2}, the droplets are so small there is a marked reduction in the throw range. Below 100 lb/in.^{2}, the spray angle starts to collapse and the droplet size becomes so large the agent will pass through the flame front without completely vaporizing and decomposing. This results in a reduction in agent efficiency.

Using the constant pressure system results in the best overall spray characteristics for Halon 2402. With a constant pressure system, the pressure can

237

be lowered or raised depending on the line losses. As the flow rate increases, the pressure would be increased to overcome the increased line losses.

Each type of nozzle tested had advantages and disadvantages. The following is a description of each nozzle tested and the test results.

The water nozzle (Figure 66) was used during medium-scale fire testing. Two different nozzles were used. The nozzles were basically the same internally. One nozzle had a row of spinning teeth through which the agent passed. The other nozzle had a set of fixed teeth. Inside the nozzle were a number of restrictions which extended the agent through different steps. This resulted in small exit pressure and large droplets being formed. When the nozzle was set to straight stream, large undefined drops exited the nozzle. As the large drops traveled through the air they would break up to large droplets (3/8 to 1/2 inch in diameter). This setting would only be efficient on a very large fire. On fog setting, the teeth physically break up the drops, giving small droplets with very little throw range. During testing, the nozzle with the fixed teeth extinguished fires more efficiently.

Halon 2402 seemed to affect the internal parts of the nozzle. During testing, the mechanisms would not turn freely; as testing continued, a definite interference was created. After the testing was completed, the nozzles were unable to function properly.

Figure 67 depicts a drawing of the water spray nozzles tested. Different exit diameters were tested. During fire testing, only one nozzle diameter was tested, the largest size of nozzle available off the shelf which could easily be adapted to the extinguishing system. The other nozzles were used in different concentration tests. During medium-scale tests, the nozzle (Model 1HD) developed by Spraying Systems was used to suppress pool fires. This nozzle has an exit orifice of 0.328 inch and produces an application rate of 4.2 lb/s. Cylinder pressure was set at 150 $lb/in.^2$, and 50 feet of 3/4-inch hose produced the stated application rate.

The nozzle was tested both with and without the internal body vane. Removal of the vane did not change the flow rate but did change the spray
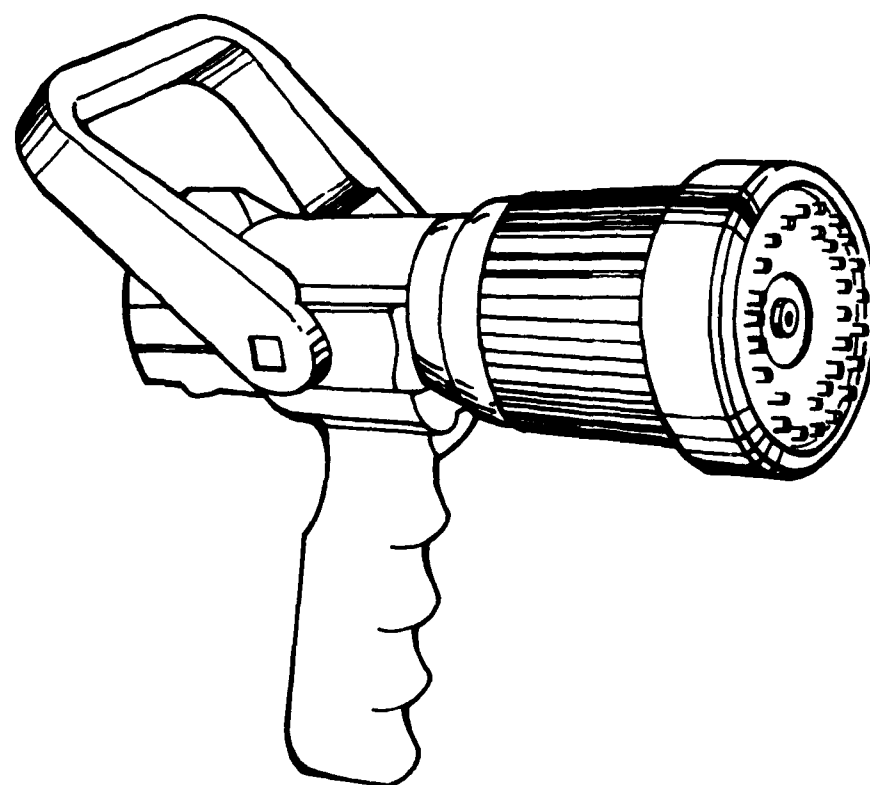
Figure 66.   Water Nozzle.
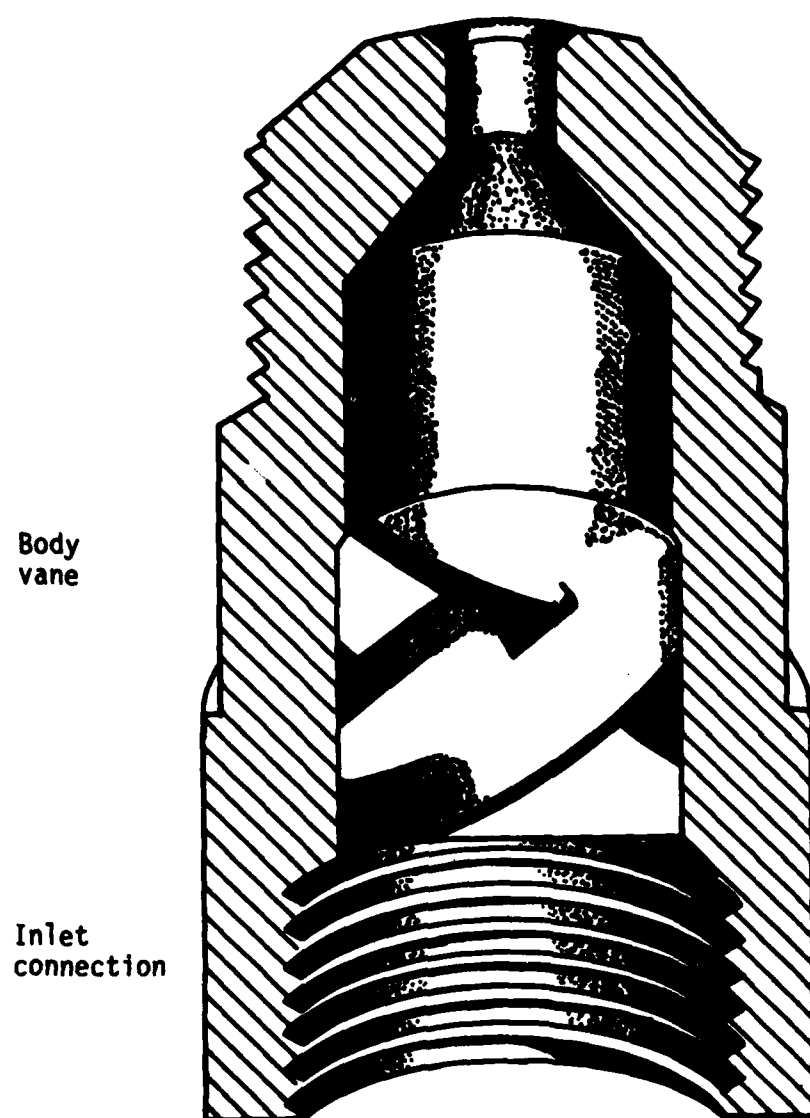
Body
vane

Inlet
connection

Figure 67.   Water Spray Nozzle.

angle. With the vane, the spray angle dropped to 30 degrees. The action of the vane rotated the agent and produced small (0.05-inch) droplets. The large spray angle and small droplets resulted in a short (15-foot) throw range. Removing the vane doubled the throw range. This nozzle did not perform well in outdoor windy conditions. Under calm conditions, the nozzle worked very well until the fire became very large and the throw range became a factor. This nozzle would work very well in a fixed system which could be mounted close to the fire hazard with restricted air movement. One example is a fixed fire system surrounding a bank of transformers.

The plain tip nozzles (Figure 68) were used during medium-scale and large-scale testing. Orifice diameters from 0.25 to 0.5 inch were tested. A 0.5-inch nozzle was the most effective nozzle for suppressing the 3-D fire apparatus. When using a wheeled extinguisher with 50 feet of 0.75-inch fire-hose charged to 150 lb/in.^{2} with a constant feed nitrogen system, the application rate was 9.0 lb/s. At this charge pressure, Halon 2402 would exit the nozzle with a 5-degree cone. When the cone reached a diameter of 1 foot, the diameter remained constant. In this configuration, the 0.5-inch nozzle can spray agent 45 to 55 feet under calm conditions. As the exit area was reduced, the spray angle increases. With the 0.25-inch nozzle, the spray angle increased to approximately 25 degrees and a 3-foot diameter cylinder of agent formed.

After testing the 0.25-inch nozzle, the exit was modified to include a diverging exit. In a length of 1 1/4 inches, the diameter changed from 1/4 inch to 9/16 inch. This was done in an attempt to obtain a larger spray angle. Testing indicated no change in spray angle by adding the diverging exit. To check this, a 5/16-inch diameter nozzle with a diverging exit was tested. The results were the same. There was no increase in spray angle by adding the diverging exit.

With the very small spray angles encountered using this type of nozzle, a long diverging nozzle (approximately the size of the spray angle) would be needed to affect the spray angle. With the diverging nozzle tested, the exit angle was larger than the spray angle, resulting in very small wall effects from the nozzle exit. Without the wall effect to enlarge the spray angle, there was no change in spray angle noted.
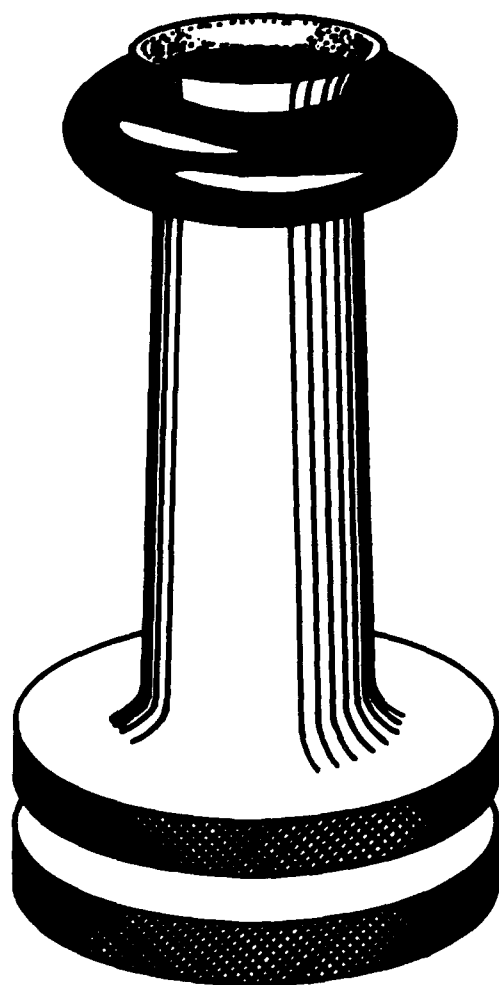
Figure 68.   Plain Tip Nozzle.

The penetrator tool (Figure 69) was designed to inject halon into the interior of an aircraft. In this situation, a long throw range was not needed. When used to fight outdoor fires, the large spray angle generated by the eight exit orifices greatly reduced the throw range. Internal obstruction also reduced the exit pressure of the agent. This resulted in larger droplet sizes and a smaller throw range. When using Halon 1211 a full cone of agent was produced. With Halon 2402 eight streams of agent were produced. This nozzle works well when used as it was designed. The nozzle will suppress an exterior fire and can be used to fight close fires or for protection.

The final type of nozzle tested was the standard Air Force nozzle (Figure 70) used for Halon 1211. With a converging/diverging configuration, the internal structure of this nozzle was the same as the plain end nozzles. The standard nozzle had a minimum internal diameter of 0.25 inch and an exit diameter of 1.0 inch. For some of the tests, another nozzle was modified by drilling the diameter to 0.5 inch. The 0.5-inch nozzle had the same spray characteristics as the 0.5-inch plain end nozzle when using the wheeled extinguisher.

During the 2200 ft^2 testing, this nozzle was used with the P-13 firetruck. The storage tank pressure was 180 lb/in.^{2} during the extinguishment of the fire. The resulting application rate was 10.2 lb/s. For this application rate, the system characteristics were the following:

1. 100 feet of hose.
2. 1-inch hose diameter.
3. 180 lb/in.^{2} minimum storage pressure.
4. Air Force nozzle with a 0.5-inch orifice.

The agent throw range for this configuration was 60 to 70 feet under calm conditions.

During testing, the spray and throw characteristics between the 0.5-inch brass converging plain tip nozzle and the modified Air Force halon nozzle with a 0.5-inch minimum internal diameter were very small. Therefore, the existing
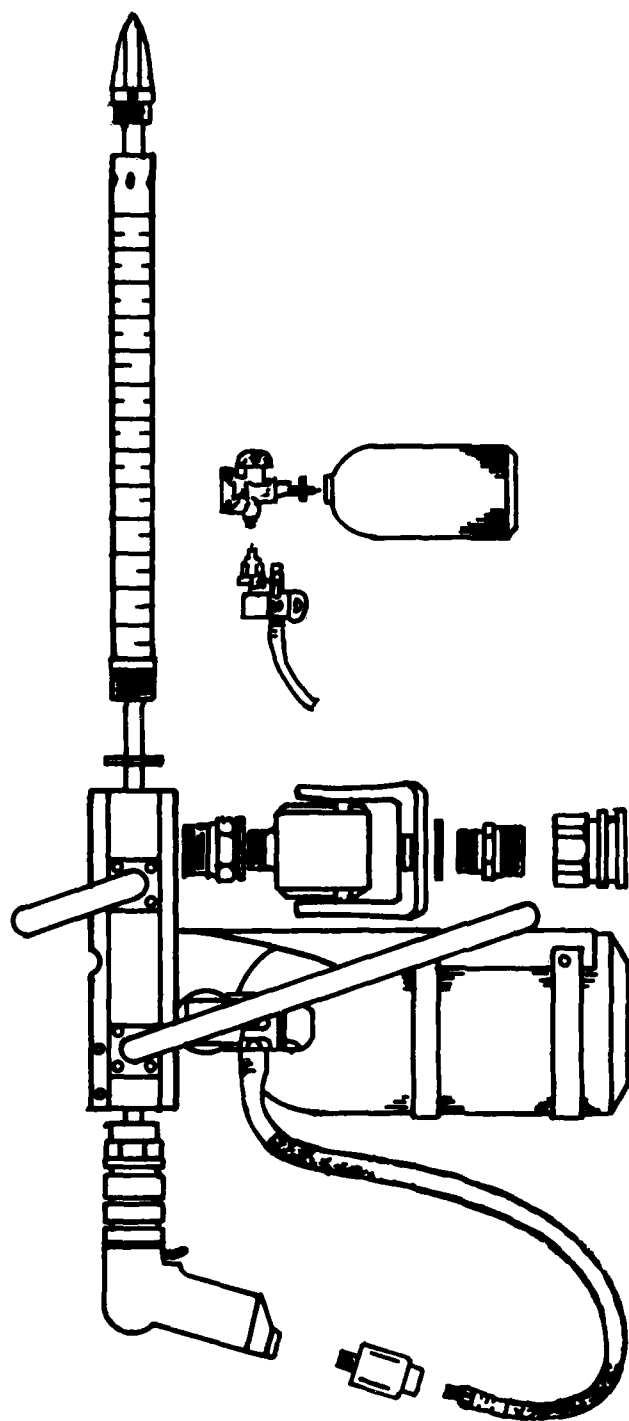
Figure 69. The Penetrator Tool for Injection of Halon into Aircraft Interior.

Figure 70. Standard Air Force Spray Nozzle.

constant-pressure halon extinguishing systems in current use in the military could be used with Halon 2402 with minimal modifications. With wheeled or portable fixed-pressure extinguishers, the fill ratio would need to be changed before the system could use Halon 2402.

SECTION VII
CONCLUSIONS

With the wide range of testing done, a broad base of information on Halon 2402 has been gathered. This information has shown Halon 2402 to be a very effective firefighting agent. One of the main advantages of Halon 2402 is the fact that it is a liquid under most conditions. If the ambient temperature is above 117 °F, then Halon 2402 will start to boil. Because Halon 2402 is normally a liquid, it is stored and shipped in 55-gallon drums. This allows for field charging of extinguishing systems with a hand-operated pump.

The military specification generated for Halon 2402 will ensure that only high quality firefighting agent will be purchased. Halon 2402 can easily integrated into the military system. The integration can be accomplished with minor equipment modifications on all current equipment presently using Halon 1211. The modifications, details of which are discussed in previous sections and outlined below, include the following:

1. Change the fill ratio on fixed pressure systems.
2. Modify the nozzle.
3. For some systems the hose size may need to be changed.
4. Reevaluate charge pressures.

The performance data indicates that maximum throw range of Halon 2402 is achieved when the droplets are 0.2 inch and larger. For each given nozzle exit pressure, there is an optimum system pressure to obtain the maximum throw range. Above that pressure, the droplet size becomes too small; below that pressure, the available energy in the agent stream is reduced. The system described in the large-scale pool fires resulted in the best overall spray characteristics. This system produced a stream of Halon 2402 with 1/4- to 7/16-inch droplets forming a cylinder 12 to 18 inches in diameter. With a throw range of 60 to 70 feet, the modified Air Force P-13 halon nozzle described in Section II was very effective against all sizes of fires. With small fires, the agent efficiency was reduced but the fire was quickly suppressed. When a fire is suppressed with Halon 2402, there is a lag between the time of agent application and extinguishment. This lag time is produced

because Halon 2402 is a liquid and needs to be in vapor form to extinguish a fire. Firefighters will need to be retrained to use the lag time and inerting effect of Halon 2402 to the maximum extent.

Though the toxic effects of Halon 2402 are not thoroughly understood for a wide range of application scenarios, toxicity could be a major impediment to its use. It is generally known that neat Halon 2402 is more toxic than neat Halon 1211, which in turn is more toxic than neat Halon 1301. Halon 2402 should not be used in flooding situations where there are personnel present.

By using different nozzles and exit pressures, Halon 2402 can be used in all types of systems, from unoccupied warehouses to large truck mounted nozzles. In windy outdoor conditions, the heavy vapors, liquid droplets, and fuel inerting ability of Halon 2402 are advantageous.

Detailed conclusions on Halon 2402 properties, uses, drawbacks, and advantages are contained at the end of most sections in the text.

REFERENCES

1. Purdue University, **Final Report on Fire Extinguishing Agents for the Period September 1, 1947 to June 30, 1950,** Contract W44-009-eng-507 Army Engineers Research and Development Laboratories, Ft. Belvoir, Virginia.

2. Hebenstreit, L. V., DeRouville, M. and Rogers, K., **Development of Full Scale Pyrotechnic Generated Gas Discharge Fire Extinguishing System,"** Technical Report AFAPL-TR-69-66, Walter Kidde and Company, Belleville, NJ, for Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, OH, AD860068.

3. Gann, R. G. (editor), **Halogenated Fire Suppressants,** ACS Symposium Series 16, American Chemical Society, Washington, DC, 1975.

4. **Fluobrene 2402, Dibromotetrafluoro-ethane,** Montedison, Industrial Products Division; **Halon 2402, Fluorobrene, Dibromotetrafluoroethane,** Ausimont, Montedison Intermedi a Rusiliari Chimici per L'industria.

5. Engibous, D. L., and Torkelson, T. R., **A Study of Vaporizable Extinguishants,** Wright Air Development Division, WADC-TR-59-463, AD 239 021, January 1960.

6. Plugge, M. A., Wilson, C. W., and Zallen, D. M., **Fire Extinguishing Agents for Oxygen-Enriched Atmospheres,** ESL-TR-85-26, Engineering and Services Laboratory, Tyndall AFB, Florida, December 1984.

7. Hirst, R., and Booth, K., "Measurement of Flame-Extinguishing Concentrations," **Fire Technology,** Volume 13.

8. Manheim, J. R., **Evaluation of Halon 1301 for Fire Suppression in Oxygen-Enriched Atmospheres,** Wright-Patterson AFB, Ohio.

9. Beeson, H. D., and Zallen, D. M., **Three-Dimensional Fire Extinguishant,** ESL-TR-85-62, Engineering and Services Laboratory, Tyndall Air Force Base, Florida, September 1985.

10. Geyer, G., **Equivalency Evaluation of Firefighting Agents and Minimum Requirements at U.S. Air Force Airfields,** Technical Report DOT/FAA/CT-82/109, Federal Aviation Administration, Atlantic City Airport, New Jersey, October 1982.

11. Alger, R. S., Laughridge, F. I., Wiltshire, L. L., McKee, R. G., Johnson, W. H., Alvares, N. S., **Characteristics of Kinematic Jet Fuel Fires, Cascading and Rod Fuel Geometries,** Technical Report DOD-AGFSRS-76-3, Wright-Patterson Air Force Base, Ohio, October 1975.

12. Wiersma, S. J., Alger, R. S., McKee, R. G., Johnson, R., **Design of a Cascade Fire Apparatus for Testing Countermeasure Effectiveness,** Technical Report DOD-AGFSRS-76-7, Wright-Patterson Air Force Base, Ohio, June 1976.

13. Cuthbertson, R. H., **Aircraft Skin Penetrator and Agent Applicator,** Report ESL-TR-84-12, Engineering and Services Laboratory, Air Force Engineering and Services Center, Tyndall Air Force Base, Florida, January 1984.

REFERENCES (CONTINUED)

14. Choudhury, P. Roy and Gerstein, M., "Analysis of a Fuel Spray Subjected to Coupled Evaporation and Decomposition," **Nineteenth Symposium (International) on Combustion**, The Combustion Institute, 1982, pp. 993-997.

15. Mellor, A. M., "Current Kinetic Modeling Techniques," **General Motors Research Laboratory Symposium, Emissions from Continuous Combustion Systems**, No. 10, (1971).

16. Frossling, N., "Uber Die Verdunstung Fallender Tropfer," **Gerlands Beitr. Geophys**, Vol. 52, (1938), pp. 170-216.

17. Reid, Robert C. and Sherwood, Thomas K., **The Properties of Gases and Liquids**, McGraw-Hill Book Company, Inc., New York, 1958, pp. 264-273.

18. Shearer, A. J. and Faeth, G. M., **Evaluation of a Locally Homogeneous Model of Spray Evaporation"**, NASA Contractor Report 3198, Prepared for the Lewis Research Center, p. 15, 1970.

19. Pantankar, S. V., and Spalding, D. B., **Heat and Mass Transfer in Boundary Layers**, 2nd ed., Intertext Books, London, 1970.

20. Nukiyama and Tanasawa, **Transactions of the Society of Mechanical Engineers (Japan)**, Vol. 6, pp. S7-S8 (1940).

21. Swirdells, Coe, J. R., and Godfrey, T. B., **Journal of Research, National Bureau of Standards**, Vol. 48, p. 1 (1952).

22. **Tentative Standards on Halon 2402 Fire Extinguishing Systems**, National Fire Protection Association, Batterymarch Park, Quincy, Massachusetts, 1983.

23. Hougen, O. A., Watson, K. M., Ragatz, R. A., **Chemical Process Principles, Part II, Thermodynamics**, 2nd Ed., John Wiley & Sons, Inc., New York, 1947, p. 686.

24. Drew, T. B., Koo, E. C., and McAdams, W. H., **Transactions of the American Institute of Chemical Engineers**, Vol. 28, 56 (1932).

25. Tapscott, R. E., Beeson, H. D., Lee, M. E., Plugge, M. A., and Zallen, D. M., **Extinguishing Agent for Magnesium Fire, Phases I-IV**, Task Report for S.S. 3.07, Contract No. F29601-84-C-0080, Engineering and Services Laboratory, Tyndall AFB, Florida, and Naval Air Systems Command, Washington, DC, January 1986.

26. DuPont, "Freon Fluorinated Hydrocarbon Fire Extinguishing Agents," Freon **Kinetic Technical Bulletin B-4**, 15 November 1954.

27. Meyer, Eugene, **Chemistry of Hazardous Materials**, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1977, p. 188.

28. **Occupational Safety and Health Standards, Subpart Z - Toxic, Hazardous Substances**, 29 CFR 1910.1000.

REFERENCES (CONTINUED)

29. **TLVs, Threshold Limit Values and Biological Exposure Indices for 1985-86**, American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio, 1986.

30. Van Stee, E. W., **A Review of the Toxicology of Halogenated Fire Extinguishing Agents**, Report AMRL-TR-74-143, Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio, November 1974.

31. Chambers, W. H., **An Investigation of the Toxicity of Proposed Fire Extinguishing Fluids**, Medical Division Research Report 23, Chemical Corps, U.S. Army Chemical Center, Maryland, October 1950.

32. Rainaldi, N., "Advance Report on Halon 2402," presented at the NFPA Annual Meeting, May 16, 1969, New York, N. Y. An abstract is contained in **Fire Protection by Halons**, NFPA Publication Number Spp-25-1975, pp. 79-87.

33. Stewart, R. D., Hosko, M. J. Peterson, J. E., Newton, P. E., Baretta, E. D., and Dodd, H. C., **Effects of Low Concentrations of 1,2-Dibromotetrafluoroethane (Halon 2402) on Human Performance**, Report No. ENVIRON-MED-MCW-HALON-1-73, Department of Environmental Medicine, The Medical College of Wisconsin, July 1973.

34. Gaydos, J. C., Colonel, MC, Director, Occupational and Environmental Health, U.S. Army Environment Hygiene Agency, Aberdeen Proving Ground, Maryland, memo to HQDA(DASG-PSP-E), Washington, DC, 9 May 1985.

35. Zielinska-Psuja, B., Orlowski, J., and Marzantowicz, E., "The Appraisal of the Toxicity of Halon 2402," **Bromat. Chem. Toksylkol.**, Vol. 17, pp. 45-49 (1984).

36. McDougal, J. N., Jepson, G. W., Clewell, H. J. III, and Andersen, M. E., "Percutaneous Absorption of Chemical Vapors, Paper No. 21, **Proceedings of the 15th Conference on Environmental Toxicology**, 1985.

37. Rainaldi, R., **An Appraisal of Halogenated Fire Extinguishing Agents**, Proceedings of a Symposium, 11-12 April 1972, National Academy of Sciences, Washington, DC, 1972, pp. 79-90.

38. Sax, N. I. and Lewis, R. J. Sr., **Rapid Guide to Hazardous Chemicals in the Workplace**, Van Nostrand Reinhold Company, New York, 1986.

39. Ille, G., and Springer, C., **The Evaporation and Dispersion of Hydrazine Propellants from Ground Spills**, CEEDO-TR-78-30, Civil and Environmental Engineering Development Office, Air Force Systems Command, Tyndall AFB, Florida, August 1978.

40. Mackay, D., and Matsugu, R. S., "Evaporation Rates of Liquid Hydrocarbons on Land and Water," **The Canadian Journal of Chemical Engineering**, Vol. 51, pp. 434-439 (1973).

41. Sutton, O. G., **Micrometeorology**, McGraw-Hill, New York, 1953.

REFERENCES (CONTINUED)

42. May, J. H., Allen, F. S., Ondrias, M. R., Tapscott, R. E., Beeson, H. D., and Zallen, D. M., "Raman Studies of Fire Retardants," **American Chemical Society Division of Fuel Chemistry, Preprints of Papers**, Vol. 31, pp. 122-125, 1986.

43. Cecich, T. F., "The Use of Halons as Fire Extinguishing Agents," **Professional Safety**, January 1985, p. 28.

44. Turner, B. D., **Workbook of Atmospheric Dispersion Estimates**, Revised Edition, U.S. Department of Health, Education, and Welfare, Public Health Service, Cincinnati, Ohio, 1966.

45. Kahler, J. P., **Calculating Toxic Corridors**, Headquarters Air Weather Service, Scott AFB, Illinois, November 1980.

46. Duffie, J. A., and Beckman, W. A., **Solar Engineering of Thermal Processes**, John Wiley & Sons, New York, 1980, pp. 10-13.

47. Gloria, C. M., **Distribuzione dei Vapori di Fluobrene in Aria**, University of Milan, undated.

48. Beaudry, J. P., Tapscott, R. E., Zallen, D. M., **Fire Protection System for Hardened Aircraft Shelters**, Final Report for S.S. 3.06, Contract No. F29601-84-0080, Engineering and Services Laboratory, Tyndall AFB, Florida, August 1986.

49. **Environmental Law Handbook**, 8th Edition, Government Institutes, Inc., Rockville, Maryland, 1985.

50. **Hazardous Materials Guide, Shipping, Materials Handling and Transportation**, 1985 Edition, J. J. Keller & Associates, Inc., Neenah, Wisconsin.

51. **Test Methods for the Evaluation of Solid Wastes, Physical/Chemical Methods**, EPA Publication SW-846, 2nd. Ed., 1982, as amended by Update I (April, 1984) and Update II (April, 1985).

52. Lee, M. E., Tapscott, R. E., and Zallen, D. M., **Effective Disposal of Fuel Cell Polyurethane Foam**, NMERI WA4-7, April 1986.

53. Daniels, S. L., Kuszaj, J. M., and Martin, J. B., **Environmental Progress**, Volume 1, p. 231 (1982).

54. Zallen, D. M., **Potential Hazards of Using Halons for Fuel Fires Involving Munitions**, Report ESL-R4TR-81-27, Engineering and Services Laboratory, Air Force Engineering and Services Center, Tyndall Air Force Base, Florida, February 1981.

55. **Toxic Substances Control Guide, Manufacturing, Processing and Distribution**, J. J. Keller & Associates, Inc., Neenah, Wisconsin, 1984.

56. **Occupational Exposure Guide, Identification, Classification and Regulation**, J. J. Keller & Associates, Neenah, Wisconsin, 1984.

REFERENCES (CONCLUDED)

57. Telliard, W. A., "The Consent Decree Pollutants and Their Analysis by GC/MS," **Spectra**, Vol. 10, pp. 4-10, 1986.

58. **The Ozone Layer**, Biswas, A. K., ed., Pergamon Press, New York, 1979.

59. **Stratospheric Ozone and Man**, Vol. 2, Bower, F. A., and Ward, R. B., eds., CRC Press Inc., 1982.

60. MIL-M-12218C, as amended, **Military Specification Monobromotrifluoro-methane (Liquified), Technical Grade for Fire Extinguisher.**

61. MIL-B-38741, as amended, **Military Specification Dibromodifluoromethane, Technical.**

62. MIL-D-4540B, as amended, **Military Specification Dibromodifluoromethane, Technical.**